Technical University of Denmark

Mikkel Ørum Wahlgreen s042157
Daniel Esteban Morales Bondy s051976

Sensor Based Robot Control

Bachelor thesis, November 2009

DTU Electrical Engineering
Department of Electrical Engineering

Sensor Based Robot Control

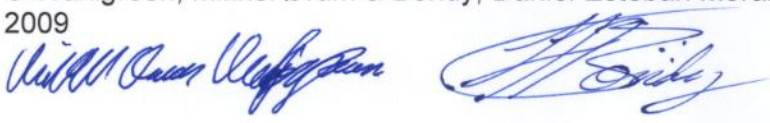
Report written by:
Mikkel Ørum Wahlgreen s042157
Daniel Esteban Morales Bondy s051976

Advisor(s):
Nils Axel Andersen
Ole Ravn

DTU Elektro
Technical University of Denmark
2800 Kgs. Lyngby
Denmark

studieadministration@elektro.dtu.dk

Project period:	24-08-09 — 30-11-09
ECTS:	15 points
Education:	B. Science
Field:	Electro technology
Class:	Public
Edition:	1. edition
Remarks:	This report is submitted as partial fulfillment of the requirements for graduation in the above education at the Technical University of Denmark.
Copyrights:	© Wahlgreen, Mikkel Ørum & Bondy, Daniel Esteban Morales, 2009



Abstract

This projects describes the efforts to create a solution to an industrial problem. A 6-joint, 6 degree of freedom robot arm was used to simulate the deburring of a metal plate. A 6-axis force/torque sensor was placed at the tool tip, allowing force regulation in the process. A mock-up of a deburring machine was built, and the robot managed to simulate the deburr proces of four sides of a metal plate.

Abstract

Gennem dette projekt er bestræbelserne på at finde en løsning på en industriel problematik beskrevet. En 6-leds, 6 friheds grader robot arm var brugt til at simulere afgratningsprocessen af en metalplade. En 6-akselede kræft/moment sensor blev placeret for enden af robotten, hvilket gav en tilbagekobling i processen. En træmodel af en afgratningsmaskine blev bygget og robotten var i stand til at simulere afgratningsprocessen på fire kanter af metalpladen.

Foreword

We would like to thank the people at AUT DTU, especially the following people:
Nils Axel Andersen and Ole Ravn, our supervisors.
Henrik Poulsen, who built our mock-up of the deburr tool.

Also a thanks to Universal Robots for letting us borrow their robot, especially Esben H. Østergaard, who helped with troubleshooting.

Last but not least a thanks to Rene Bondy, who showed us how deburring is done in the industry, and providing positive feedback.

Contents

1 Introduction **6**

2 Problem Statement **7**

3 Problem Delimitation **8**

4 Theory **9**
4.1 Deburring . . . 9
4.1.1 Robot deburring . . . 9
4.1.2 Tool Considerations . . . 13
4.1.3 Safety Considerations . . . 15
4.2 Kinematics and Mathematics . . . 15
4.2.1 Denavit-Hartenberg Notation . . . 16
4.2.2 Path generation . . . 18
4.3 Python programming . . . 19
4.4 Linear control . . . 19

5 Equipment description **21**
5.1 Force sensor . . . 21
5.2 The UR-6-85-5-A robot . . . 22

6 Implementation **25**
6.1 Analysis of Solutions . . . 25
6.2 Method Implementation . . . 25
6.2.1 Deburr Process . . . 28
6.2.2 Linear control design and kinematic values . . . 29

7 Programming the robot **32**
7.1 Functions and their uses . . . 32
7.2 User manual for the program . . . 33

8 Calibration and Test **35**
8.1 Test of communication speed . . . 35
8.2 Force feedback during deburr . . . 36

8.3 Noise on the force sensor 37

9 Errors in the robot **40**

10 Conclusion **42**

11 Future Work **43**

References **45**

A Force error on the axes **46**

B CD List of Contents **56**

C Drawing of force sensor **58**

D Drawing of the victim element **60**

E Drawing of the deburr tool model **62**

F Source code **65**

F.0.1 maindeburr.py 65
F.0.2 connectionregulatortest.py 76
F.0.3 force.py 92
F.0.4 force_test.py 95

Reading guide

All of the concepts and theories needed to understand how the solution presented in this report works can be found in the theory section. It is not required to have a deep understandig of the presented concepts, although if the reader wishes to have more knowledge related to these topics, it is recommended to read the references, especially [OI09].
This report is written by two Bachelor of Science students at DTU and is meant to document a test-bench solution for a given problem. This problem is to simulate a deburr process of a plate of aluminium with the UR-6-85-5-A robot. To be able to read and understand this report, the reader should have some basic knowledge about topics concerning control of robots, math, and programming languages. The following topics are essential for a clear understanding of the described solution:

- Math taught to first year Bachelor students concerning changing coordinates from one coordinate system to another
- Physics concerning gravitation forces and forces affecting two objects pushed against each other
- Basic knowledge in programming languages like C and Python. It is not a must for the reader to know Python, since it is easy to compare to the syntax of C or Matlab
- How a robot arm with 6 joints moves around in its workspace
- Linear control designs of the single-input/single-output[1] type
- How a transducer sensor works

Anyone is welcome to read the report even if they do not have knowledge in all the fields mentioned above, but it is not guaranteed that they will understand everything described throughout the report. The intended readers of this report are the supervisor of the project and the sensor at the bachelor exam, as well as any potential buyer of the UR-6-85-5-A robot, the producer of the robot, and other people with a interest in our project.

[1] Commonly known as SISO

Reviewing or Reading

Depending what the goal for reading this report is, there are two guidelines for going through the report:

- The report can be read from one end to another, in order to ensure a thorough understanding of the content of the report, and the effort invested in the project
- Or the highlights of the report can be read, which are the problem statement in chapter 2 on page 7, the problem delimitation in chapter 3 on page 8 and the conclusion in chapter 10 on page 42. If more understanding is needed of a certain topic, then the chapter concerning that specific topic must be consulted.

Chapter 1

Introduction

The term robot comes from the Czech word *robota*, generally translated as "forced labor"[Har], and was coined by the Czech writer Karel Capek in 1921 [Iso05]. Although robots no longer have the single purpose of forced labor that Capek once envisioned for them, doing jobs too complicated or too tiresome for the human being, is still their main appliance. One of the kinds of robot which has become common in modern industry is the robotic arm.

Robotic arms have developed greatly during the last decades and have found several uses in modern culture. Their jobs can vary greatly, serving as prosthetics, doing work in an assembly line, or even doing reparations at the International Space Station. One of the reasons their use has become more common in today's society is that their precision in movement has increased greatly. This is caused by improvements in fields of control theory, in electronical measurements and sensing, and electro-mechanics. Robotic arms are important in modern society because they can do work that a human being would not be able to.

Since the use of robot arms has become widespread, it has become important for upcoming robotic engineers to learn about them. It is essential for any robotic engineer to understand modern concepts and theories in the fields of control and regulation, physics, mathematics, programming and electronics. Not only knowledge in the individual fields is required, but also knowledge about how to integrate the different fields is needed, inorder to create solutions which help the society.

Due to the challenges and opportunities to learn, the study of the field of robotic arms offers an electronical-engineer student, a project related to said field has been chosen at the Automation and Control group at the Technical University of Denmark, as finishing exam for the Bachelor study. This project will consist in creating a solution to an industrial problem based upon sensor control of a robot arm.

Chapter 2

Problem Statement

Autonomous arms, or robotic arms, have become a common element in modern industrial processes. Their tasks have become manifold with time, which leads to a demand of better precision from the robot arms. The problem tackled in this project can be summarized in the following questions:

- How to do a delicate and precise procedure using the robot arm, a pressure sensor, and a tool
- What can be done to make the robot adaptive to the surface or the structure it is working on?
- How can vibrations be damped and/or removed in the process?

This should be done to make the arm more accurate in fields like glass cutting, engraving on metal plates and deburring.

Chapter 3

Problem Delimitation

The topics discussed in the problem statement are very wide, and can be applied to many fields of work for automatized robot arms. Therefore, certain limitations to the problem statement need to be applied.

The project is done in cooperation with the company Universal Robots (UR), which has provided AUT with a robot arm model UR-6-85-5-A. This robot arm has six degrees of freedom (DOF), six joints and has been added a six axis force/torque sensor. Since many of UR's clients want to use this model as a deburring tool, this project will focus on integrating the pressure sensor with the robot arm, and making a program for deburring work. The aim of this project is to create a solution to an industrial problem, which UR can use as marketing for their product. Because of time and budget constraints, this project will only be a testbench for the solution.
Due to the light weight of the UR-6-85-5-A, it is expected that the setup of the robot arm will be moved around to different positions in a production line. In order to reach results that are realistic compared to the actual use of the robot, the setup will not be fastened to a 100% stable armature, but will stand on a table without actually being bolted to it.

Furthermore, it is assumed that the robot will only deburr the same kind of elements in a series, i.e. it will only deburr plates of the same size, or cylinders of same diameter, and will "know" beforehand which kind of object it is to deburr. In this case, the test bench will prove that 10 cm $\times$ 15 cm aluminium plates can be deburred. From now on, these plates will be refered to as "victim elements" or "elements".

The programming of the computer will be made in the Python programming language, and will be sent to the robot arm over Ethernet, using the TCP/IP protocol, as a set of instructions. If UR find the program satisfying, they will easily be able to integrate it into their own Linux operative system.

Further, this project builds on an earlier project made at Automation and Control(AUT) by Örn Ingólfsson and Einir Gudlaugsson (see [OI09]). A pressure sensor has already been attached to the end effector of the UR robot arm, and this project is going to use their setup as start condition.

Chapter 4

Theory

Like most engineering solutions, this project combines concepts and theories from several different fields. The essential concepts used for this project will be described in this chapter, where each "field" will have its own subsection.

4.1 Deburring

This section comes from [CW76], and for further information on the topic, reading this source and [Gil99] is recommended.

Whenever one wants to cut or stamp out a piece of material, there will be a burr of some kind left on the edges. On a piece of metal, these burrs are mostly undesired, because they are often sharp and can cut personnel or other materials during handling. To get rid of these burrs there are several solutions. It can be done by manually using hand tools or machines, or it can be done automatically by machines or robots. If the deburring is to be repeated during a production of thousand objects, then the automated approach is preferred, but only if the objects are not too complex. If the latter is the case, then a hand tool is preferred, due to the fact that machines cannot get the job done if the holes or edges are too small or too close to something else.

If the objects have to be deburred by hand, it can be done with several different tools, the most common are shown in figure 4.1(a), but for manual deburring it is also possible to use machines like the one shown in figure 4.1(b) or like the drill shown in figure 4.1(c) and figure 4.1(d). For automated deburring it is possible to use NC/CNC machines with all kinds of specialized deburring tools or brushes, trimming presses, edging machines for sheet metal, end-finishing machines for tubes and bars, single purpose machines designed for specialized deburring, gear deburring machines or robotic deburring.

4.1.1 Robot deburring

For robotic deburring, the typical applications use industrial robots to deburr large objects, a specific part or parts of a close geometric family. Precision deburring is not preformed

(a) The most commonly used hand tools for deburring

(b) Small machine for deburring and chamfering

(c) Tool mounted on a drill for chamfering/deburring holes

(d) A chamfer tool for deburring two edges of a workpiece

Figure 4.1: Different hand tools or machines used for deburring, either manually or automaticaly

by robots due to the fact that most of them are not capable of performing precision movements. When robots are used to deburr large objects, the robot moves around the object, but when deburring smaller objects with a low weight the robot moves the object around between the tools.

Depending on the assignment, the robot should have at least 5 or 6 joints, high accuracy and repeatability, continuous-path capability, the capability for easy and quick tool or spindle changes, rigidity and low inertia. Extra desirable features could be easy off-line programming, circular interpolation, and the ability to translate movements to similar features on the same workpiece.

To achieve a good repeatability for a robot in the industry, there is a good guideline in a combination of the following factors:

- The accuracy and positioning repeatability of the robot mechanism
- Consistency in positioning the edges of the workpiece to a reference surface (clamping force can significantly deflect some parts)
- Nature of the edge before deburring (burr uniformity, thickness, and location consistency)
- Repeatability of the deburring tool in the robot holder
- Repeatability and accuracy of the cutting tool geometry

When working with a precision robot, the robot is often built as a point-to-point machine. Modern control methods are being used now to control robots, which leads to continuous-path robots and controlled-path robots.

The point-to-point mode means that the robot moves from one point to another in space with the end effector and the motion and speed of each joint of the robot cannot be predicted. Each time a point is defined all the joint positions must be saved into a memory block. When the robot moves, some of the joints move into position before others and therefore the path between two points cannot be predicted easily.

Continuous-path mode means the operator is often able to grab and move the robot from one place to another and thereby teaching the robot how to behave. Often this data is read into a memory at continuous-time with a sampling rate from 60 to 80 Hz.

When the controlled-path mode is used, the path between each point of movement is calculated by a computer program doing replay after the points are put into the program, much the same way as with continuous-path robots. These points are then saved as a location of the tool center instead of the position of each joint.

Controlled-path robots often come with one or more different interpolation types like joint, linear, and curvilinear interpolation.

- Joint interpolation means that all the joints reach their position at the same time.
- Linear interpolation results in a linear motion of the tool center point.

- Curvilinear interpolation moves the tool center along a desired curvature.

During the actual programming of a robot, the operator can be placed next to the robot and control the movements with a joystick or other interfaces (On-line), or he/she can do the programming elsewhere like with a NC/CNC[1] machine (Off-line). The on-line programming is often used as a trial and error method when the robot has to work with simple parts and the on-line programming can be used with an off-line program that needs one or more corrections.

Using on-line programming raises some issues, like shutdown of production during programming, different equipment may block sight during programming and precision adjustments cannot be done and complex parts may be time consuming to program for precise results. For off-line programming the operator must be able to tell the program about weight of tools or forces done by cutting, and therefore compensate for robot arm deflections.

For robot deburring there are three philosophical approaches to accommodate for robot inaccuracies and workpiece variations to obtain more precise results:

Compliant approach This means that the tools mounted on the robot are mounted in a setup which adds extra compliance in one or more directions of the robot than the robot gives. Rigidity in a setup like this is the key to success, but also fast servos could help the system to compensate for it, but these ideal servos do not exist.

Fine-tuned robot approach This applies that the servos and resolvers have to be fine tuned, which can increase robot accuracy by a factor of two or three. This slows down the system a bit and also risks to put the servos in a overload position, when trying to reach a specific position. Theoretically, this approach is the most accurate, but due to workpiece variations, the need to minimize chatter and maximize reliability, this approach is discarded in most scenarios. Every time something happens to the robot, like maintenance or smaller accidents, all the programs have to be retaught and reprogrammed.

Force feedback approach This approach is more established due to the use in other applications, but is not used for most parts because of the difficulties to define and control the dynamic effects. Moreover, force feedback is seen as one upcoming solution to robotic inaccuracies, workpiece tolerance variations, and incorporation of on-line databases and off-line programming. There are four constraints preventing the more frequent use of force feedback:

- The robotic system cannot respond quickly enough for many needs
- The dynamic response of the robot system is difficult to define for all arm positions

[1] Numerical Controled/Computer Numerical Control

- General algorithms that provide the robot logic are difficult to generalize for three-dimensional curvilinear geometries having variable burr size and fluctuating part geometries
- Robot compliance affects sensor data

Force sensing is often used for simple tasks together with a fettling device, where the variations of the burrs are very small and the movement is in straight lines. This will work well as long as the burrs do not change much in dimensions. If the burrs change, the robot does not know how the burr has changed and ends up going too close or too far away from the workpiece leaving a mark.

Wear and tear of the tool can also change the parameters for the force sensing system. Depending on the tool and setup used for the process, the force sensing can be used to measure wear of the tool. This can be done by putting the tool into a hole with an already known size and then pushing against the sides, thereby finding the size of the tool. Comparing the new size to the one before the robot started, the process will yield the wear of the tool. The offset is then fed into the program. A simpler method is to feed a constant offset into the program, but the main idea is to automatically adjust to wear of the tool at all times.

The geometric shape of the workpiece also plays a role in the deburring quality, cost, and programming difficulty. It gets easier with more straight lines without any bending or curves and harder if there are a lot of shallow areas, small bends, and holes in difficult areas, which need deburring in the same process.

When a specific workpiece is the target for the operation, it must be considered whether the robot has to handle a tool or handle the workpiece. A robot can handle a maximum of weight at the tool tip and this confines the size of a tool or a tool together with the workpiece. If the robot is equipped with the tool, then the workpiece has to come to the robot on a turning table, a conveyor belt, or similiar. A fixture must lock the workpiece in a known orientation and a change in the workpiece shape or size needs its own fixture and more can be needed to have the robot work continuously.

If the workpiece is light, the robot will also have the possibility of lifting the workpiece and maneuver it around between one or more fixed tools. The robot can either deliver the workpiece to a tool or pass the workpiece over the tool tip. When the process is done the workpiece can be passed on to another conveyor belt or the like, and the robot can grab a new workpiece. A regrip fixture can also be put inside the workspace of the robot, to give it access to handle all edges of a workpiece.

4.1.2 Tool Considerations

Three approaches commonly used for toolchanging are:

- Design-integral multiple motors on the end effector (at 90° to each other) to eliminate the need for changing tools

- Change preset spindles
- Change grippers and tools

These approaches are used for changing the tool, when it is on the tool tip of the robot, not changing tools in fixed tools within the workspace of the robot. When a change of the tool is done, the motor driving the tool is often changed as well. This is easier than designing tools for one motor unit only, if the operation of the tool is changed by the tool change. It is often faster to make the change in the afore mentioned way.

Most tools used for manual deburring can be used for robot deburring, but a common fact for all tools is that they will get worn out over time and therefore need to be changed after a certain amount of runs. The deburring process will in some cases leave small burrs and these can in some cases be minimized with a second run, see table 4.1.2, especially when using cutters or chamfer tools.

Table 4.1: Combinations of first and second run tools appropriate for robot deburring

	Subsequent finishing approaches	
Principal Approach	Abrasive Rubber	Brushing
Bur balls	X	
Chamfer tools	X	
Grinding wheels		X
Reverse radius cutters		X
Abrasive rubber		X
Abrasive-filled cotton		X
Brushing		
Grinding belts		
Reciprocating files		

Some considerations about the optimum use of cutters:

- Correct contact point (errors often lead to vibrations)
- Correct contact angle (correct angle avoids secondary burrs)

- Correct path direction (incorrect direction of the tool motion relative to the rotation of the tool often results in vibrations)
- Correct path velocity (depends on type of burrs, desired quality, and other factors)
- Correct resilient mounting (compliance)

Another common tool used for robotic deburring is rotating files made of high speed steel or carbide, but these wear and also need to be changed periodically. Reciprocating or oscillating files are also used, but do not work well together with soft metals like aluminum, which tend to accumulate in the teeth of the file.

The deburring can also be done by abrasive-belt grinding, but here the chamfer size is hard to control if the grinding belt is not spring or air-loaded. Furthermore, the longer the belt is, the smaller the change in frequency. A last possibility is brushing, this leaves a smooth blend and can remove all normal burrs. It is also easy to compensate for wear without changing the result, because the result does not depend greatly on the applied force.

4.1.3 Safety Considerations

When handling robots there are seven major safety hazards in robot deburring, as follows:

1. Robot runaway.
2. Inadvertent human contact with the robot.
3. Robot's sudden release of workpiece or tooling
4. High feed rates
5. High spindle speeds
6. Noise level
7. Flying debris from broken wheels, burrs, flash, broken, wire form brushes, and sparks from grinding.

Number 1 and 3 together can end up sending a tool or workpiece flying wildly at high operate speeds. A high noise level may also require a walled installation to bring down noise levels overall in the production if workers are present.

4.2 Kinematics and Mathematics

All of the mathematical and kinematic equations used in this project were researched and established by [OI09], and therefore only a superficial explanation will be given in this section. For further reading, [Cra04] and [OI09] are recommended.

Kinematics are the basic study of how mechanical systems behave. In this project, the study of kinematics of robotic manipulators will refer to all geometrical and time-based properties of the manipulator's motion.

Kinematics are an excellent tool to obtain the position and orientation of each manipulator joint, and when used for this purpose, it is refered to as *forward kinematics*. Position and orientation are determined by assigning a reference frame to each joint. A reference frame is defined as a coordinate system with an orientation and position vector relating the coordinate system to another frame. This is useful since it allows to describe joint positions and orientation in different coordinate systems, or a single basis coordinate system, if desired. Six parameters are needed to describe an object: three position parameters, and three orientation parameters. Therefore a transformation of reference frames includes translation and rotation in one frame with respect to the other. This can be achieved through linear algebra as described in [Eis99]. Let ${}_a\underline{\underline{x}}$ be a coordinate in base $\{a_i\}$ and ${}_b\underline{\underline{x}}$ a coordinate in base $\{b_i\}$ then, following is valid:

$$ {}_a\underline{\underline{x}} = {}_a\underline{\underline{R}}_b {}_b\underline{\underline{x}} + {}_o\underline{\underline{x}} \tag{4.1} $$

where ${}_o\underline{\underline{x}}$ is a matrix defining translation from one coordinate to another, and ${}_a\underline{\underline{R}}_b$ is a matrix that rotates from $\{b_i\}$ coordinates to $\{a_i\}$ coordinates.

In robot kinematics eq. (4.1) is usually expressed as:

$$ \left[\begin{array}{c} {}_a\underline{\underline{x}} \\ \hline 1 \end{array}\right] = \left[\begin{array}{c|c} {}_a\underline{\underline{R}}_b & {}_o\underline{\underline{x}} \\ \hline 0\ 0\ 0 & 1 \end{array}\right] \left[\begin{array}{c} {}_b\underline{\underline{x}} \\ \hline 1 \end{array}\right] \tag{4.2} $$

And in a simpler form eq. 4.2 can be expressed as:

$$ {}_a\underline{\underline{x}} = {}_a\underline{\underline{T}}_b {}_b\underline{\underline{x}} \tag{4.3} $$

Matrix ${}_a\underline{\underline{T}}_b$ called the *homogeneous transform* and has the following property:

$$ {}_0\underline{\underline{T}}_N = {}_0\underline{\underline{T}}_1 \cdot {}_1\underline{\underline{T}}_2 \cdots {}_{N-2}\underline{\underline{T}}_{N-1} \cdot {}_{N-1}\underline{\underline{T}}_N \tag{4.4} $$

This allows the description of the position and orientation of the tool-tip on the robot arm in the the coordinate system of the base joint. If transformation from base $\{b_i\}$ to $\{a_i\}$ is desired, it can be done through the inverse homoegenous transform: ${}_b\underline{\underline{M}}_a = {}_a\underline{\underline{M}}_b^{-1}$

4.2.1 Denavit-Hartenberg Notation

One way of expressing the forward kinematics of the robot arm is using the Denavit-Hartenberg notation. When talking about robot arms, two kinds of joints exist:

Prismatic joint This joint has one degree of freedom and provides sliding motion along a single axis

Revolute joint This joint has one degree of freedom and provides rotating motion along a single axis

Furthermore, there are four parameters defining a link (the connection between two joints):

- *Link length*, denoted by a_{i-1}, is the mutually perpendicular line between joint axes $i-1$ and i
- *Link twist*, denoted by α_{i-1}, is the angle between joint axes $i-1$ and i
- *Link offset*, denoted by d_i, is a joint variable for a prismatic joint. In case a prismatic joint is described, the other three variables will remain fixed, and depend on the dimensions and construction of the robot
- *Joint angle*, denoted by θ_i, is a joint variable for a revolute joint. In case a revolute joint is described, the other three variables will remain fixed, and depend on the dimensions and construction of the robot

Ideally, any robot arm can be described by these four variables, and when done, it is referred to as the Denavit-Hartenberg notation. A coordinate system is assigned to each of the joints in the robot arm, this can be seen in fig. 4.2.

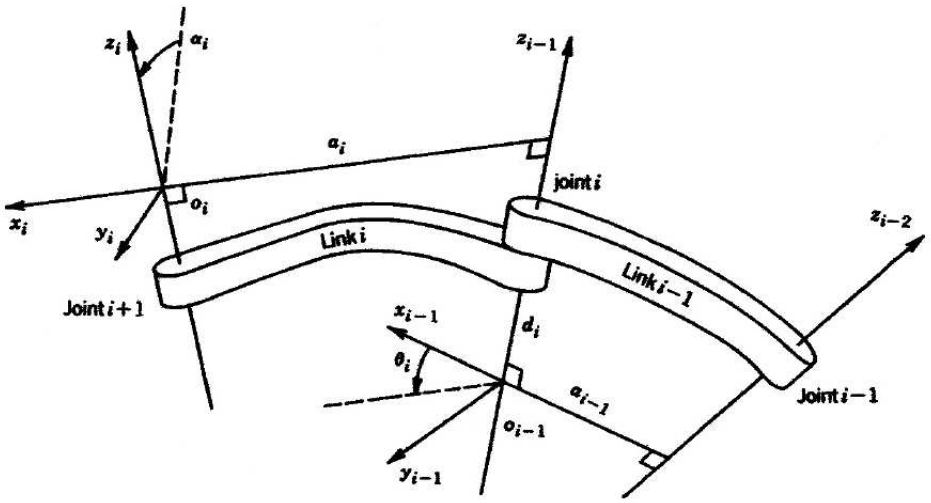


Figure 4.2: Denavit-Hartenberg frame assignment, taken from [MWS05]

The finer details of the Denavit-Hartenberg notation will not be explained here, for further information refer to [Cra04] and [MWS05]. As can be seen in fig. 4.2, the Z-axis, z_i is coincident with joint axis i, the X-axis, x_i, goes along the mutual perpendicular a_{i-1}, from joint axis i to joint axis $i-1$, and finally, the Y-axis, Y_i, is chosen according to the right-hand rule, in order to complete the i^{th} frame.

It is essential in the study of kinematics to be able to define frame $\{i\}$ in terms of frame $\{i-1\}$. This transformation is usually a function of one of the joint variables

and the remaining fixed link parameters. These four variables fit into eq.(4.3), and the homogenous transform becomes the following:

$$ {}_{i-1}T_i = \begin{bmatrix} \cos(\theta_i) & -\sin(\theta_i) & 0 & a_{i-1} \\ \sin(\theta_i)\cdot\cos(\alpha_{i-1}) & \cos(\theta_i\cdot\cos(\alpha_{i-1}) & -\sin(\alpha_{i-1}) & -\sin(\alpha_{i-1})\cdot d_i \\ \sin(\theta_i)\cdot\sin(\alpha_{i-1}) & \cos(\theta_i\cdot\sin(\alpha_{i-1}) & \cos(\alpha_{i-1}) & \cos(\alpha_{i-1})\cdot d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.5} $$

Eq. (4.5), defines the individual link transformation and accordingly, the coordinates of the end-effector of a robot can be found by inserting eq. (4.5) into eq. (4.4), giving an equation as a function of all joint variables.

4.2.2 Path generation

This subsection explains how a smooth path is generated between two points in spaced. It was the method chosen in [OI09], and since this project is a continuation of [OI09], the same method was used. A more detailed explanation can be found in [OI09]. The method cubic polynomials is used to find the desired path from an initial position to a destination in a certain amount of time. Four constraints are established in order to create a single smooth motion:

$$ p(0) = p_0 \tag{4.6a} $$

$$ p(t_f) = p_f \tag{4.6b} $$

$$ \frac{d}{dt}p(0) = 0 \tag{4.6c} $$

$$ \frac{d}{dt}p(t_f) = 0 \tag{4.6d} $$

where p_0 is the start position, p_f is the goal position and t_f is the duration of the motion. These constraints are satisfied by eq. (4.7a) and its derivatives:

$$ p(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 \tag{4.7a} $$

$$ \frac{d}{dt}p(t) = a_1 + 2a_2 t + 3a_3 t^2 \tag{4.7b} $$

$$ \frac{d^2}{dt}p(t) = 2a_2 + 6a_3 t \tag{4.7c} $$

Solving eqs. (4.7) with the constraints from eqs. (4.6) yields the following coefficients:

$$ a_0 = p_0 \tag{4.8a} $$

$$ a_1 = 0 \tag{4.8b} $$

$$ a_2 = \frac{3}{{t_f}^2}(p_f - p_0) \tag{4.8c} $$

$$a_3 = -\frac{2}{{t_f}^3}(p_f - p_0) \tag{4.8d}$$

In the case a velocity limitation is needed on the motion of the end-effector, t_f can be changed from a constant to:

$$t_f = \frac{|p_f - p_0|}{v_{max}} \tag{4.9}$$

4.3 Python programming

Python is a general-purpose high-level programming language. Its design philosophy emphasizes code readability and easy network programming. The reason Python is used as programming language is due to the fact that the code most of this project is based upon is already written in Python. The people behind this code have chosen the Python code because of the easy implementation of the TCP protocol, which the UR robot uses for communication over Ethernet. Furthermore, using this language to send commands to the robot, allows bigger flexibility than using the GUI of the robot arm (which also allows programming to a certain degree), and simplifies the integration of the force sensor data feedback. Another reason for using Python is the easy access to help via the internet and its similarities to other programming languages. Programming techniques learned from the courses 02101/02102 and 31012[2] on JAVA and C programming give a good basic understanding of how a programming language works, which is easily ported into Python.

4.4 Linear control

Linear control techniques were used to achieve precision in the movements of the robot. This section explains how a proportional-integrator regulator (PI-regulator) works. The PI-regulator has the advantage of having a good precission without the stationary error a proportional regulator (P-regulator) produces. The transfer function (in the laplace domain) of a PI-regulator can be seen in eq. (4.10)

$$G_c(s) = K_p \frac{\tau_i s + 1}{\tau_i s} = K_p \left(1 + \frac{1}{\tau_i s}\right) \tag{4.10}$$

where K_p is the proportional amplification the regulation and τ_i is the time constant. From the righthand-side of the equation, it is clear that the regulator consists of a proportional amplification of the error (the K_p factor) and the integration of the error (the $1/\tau_i s$ factor). The integrator adds a $-90°$ phase-turn, and therefore an extra zero is added at $s = \frac{-1}{\tau_i}$ [OJ06]. The control signal created by the PI-controller can also be expressed as in eq. (4.11), which is easier to implement as an algorithm in a computer.

$$[htb]u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau \tag{4.11}$$

[2]Both these courses are part of a group of obligatory programming introduction courses for almost all bachelor students at DTU

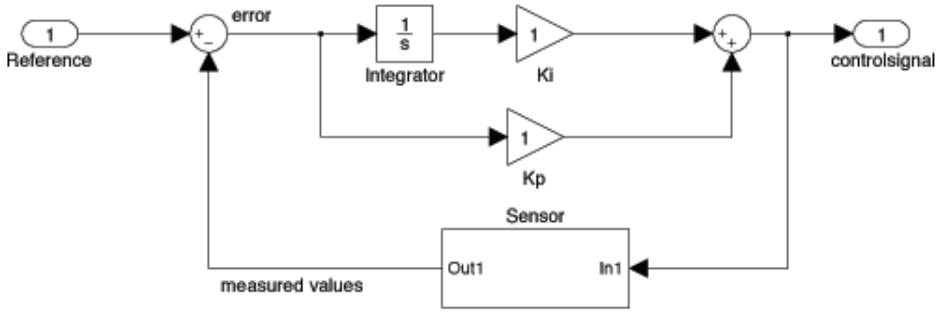


Figure 4.3: A block diagram for a PI controller, note that the error is integrated and amplified twice before it used as feedback. The reference signal is established by the designer

Further, fig 4.3 shows the block diagram of a PI-controller. This is the structure which will be used in this project.

The use of a proportional-integrator-differential regulator (PID-regulator), is also very common, but has an inherent problem in the differentiation term. That is, differentiating systems with high frequency noise, can render the whole system unstable. Therefore, this project focuses on the use of PI-regulators.

Chapter 5

Equipment description

5.1 Force sensor

In order to measure forces at the tool tip of the robot, a Mini40 sensor by ATI Industrial Automation is used. This sensor comes with a DAQ card[1] for use in a PC. The sensor is a transducer which together with the DAQ card, reads out 6-axis force/torque signals. For the connection between the DAQ card and a PC an ISA port is used. An older PC is needed to read out the force data because this form of connection is no longer used in new PC's. This setup means that the sensor cannot be connected directly to the robot through the I/O interface on the robot or inside the controller to the robot, but needs to be connected to a separate PC running Windows 2000.
The output from the sensor are 6 components, consisting of 3 forces and 3 torques (F_x, F_y, F_z, T_x, T_y, T_z), which are given in a Cartesian coordinate system around the sensor, see Appendix C.

The F/T transducer reacts to applied forces and torques using Newtons third law. The force applied to the transducer flexes three symmetrically placed beams using Hookes law:

$$\sigma = E \cdot \varepsilon \tag{5.1}$$

where σ, the stress applied to the beam, is proportional to the applied force, E is Young's modulus of the beam and ε is the strain applied to the beam.

The force sensor was calibrated before it was mounted on the robot by Ingolfsson and Gudlaugsson [OI09]. There is no apparent reason to repeat the calibration since there has been no observable change in readings from the sensor during tests, and the sensor is still in the same environment[2]. The sensors measuring capabilities can be seen in tab. 5.1

Ingolfsson and Gudlaugsson observed that large peak values appeared without any force applied to the sensor except gravity. The same observation was made during this project, but the cause of the error has not been found. This error can be disastrous for the equipment due to high correction movements sent to the robot, depending on this reading.

[1] Data Acquisition card

[2] Inside a building in normal humidity and temperatures around 23 degrees Celsius.

Table 5.1: Metric ranges and resolution of the ATI Mini40 6-axis F/T sensor

Sensing ranges		
$\pm F_x/F_y$ [N]	$\pm F_z$ [N]	$\pm T_x/T_y/T_z$ [N/m]
40	120	2
Resolutions		
$\pm F_x/F_y$ [N]	$\pm F_z$ [N]	$\pm T_x/T_y/T_z$ [N/m]
1/400	1/200	1/16000

Therefore changes have been made to the original Python code made by Ingólfsson and Gudlaugsson, see chapter 7 on page 32.

The graphical user interface (GUI) for the sensor output is written in Visual Basic 6 by [OI09] for the PC connected to the sensor. This program has been used without any changes, and although only one value, F_z, was used before, attempts to use force sensing in all three axes were made[3].

5.2 The UR-6-85-5-A robot

The Automation and Control group at DTU has received a 6-joint robot arm, from Universal Robots, in Odense, which has been made available for students to make experiments and do project work. The model of the robot is UR-6-85-5-A and is a light robot arm, weighing only 18 kg and capable of lifting up to 5 kg payloads. Details about the robot can be found in the User Manual [Roba] and on the webpage www.universal-robots.com. Only a quick introduction will be given here. Fig. 5.1 shows the different parts of the UR robot:

- A: the base of the robot, where the robot is mounted
- B: the shoulder of the robot
- C: the elbow of the robot
- D,E,F: wrists 1,2, and 3 of the robot, where a tool is attached to the robot

By coordinating movement, the robot can move freely in 6 DOF with the constraints shown in fig. 5.2, which shows that there is a cylindrical workspace along the robots base $\hat{Z}_i$ axis, where the tool point cannot work. Also, the figure shows that the robots working area is a sphere of diameter 175 cm around the base.

The robot comes with a GUI called PolyScope which is easily programmable and allows point to point movement through the definition of wavepoints. This GUI is only used in this

[3]See chapter 3.2.1 in [OI09]

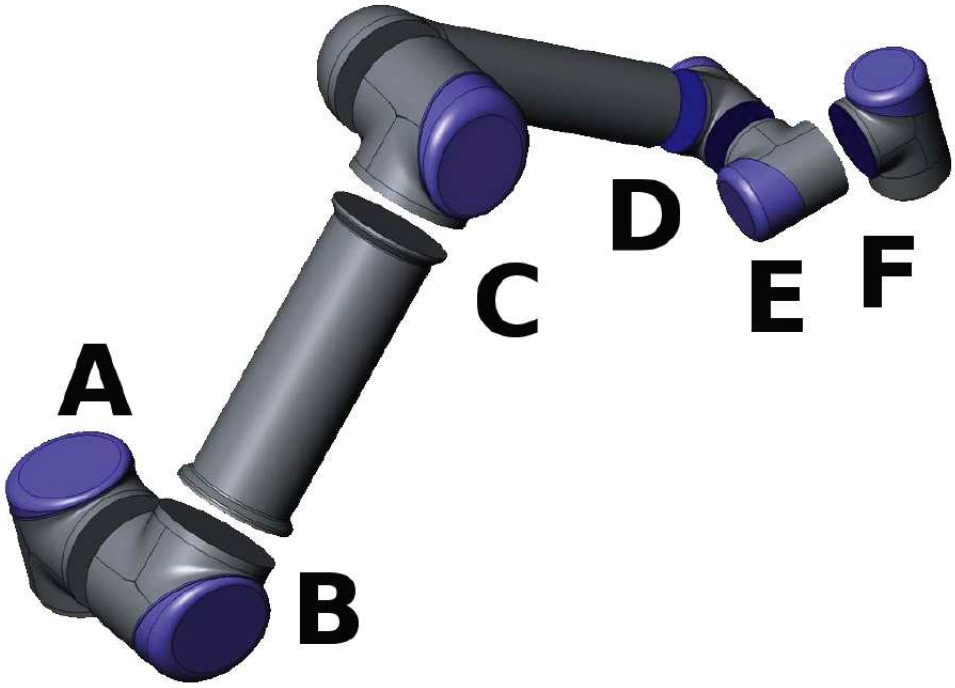


Figure 5.1: The links of the UR-6-85-5-A and its composition. Note that all the joints are revolute

project to startup the robot and to log errors from the robot arm. All other programming occurs through network protocols, as explained in sec.4.3. The GUI is a high level program that works on top of a low level language designed by UR called URScript. This script sends basic commands to the robot controller, like the command `movej(q, a =3, v =0.75, t =0, r =0)` which receives q, a vector with six joint positions, and moves to the given position with the acceleration a, velocity v, time t, and blend radius r.

The afore mentioned controller is a mini-ITX PC in the controller cabinet, and if programming at script level is desired, it must occur using a TCP/IP socket connecting to this controller from another computer. The URScript programs are executed in real-time on the URControl Runtime-Machine (RTMachine), which communicates with the controller at a frequency of 125 Hz.
The mount flange of the robot can be seen in fig. 5.3.

Many different kinds of tools can be mounted on this flange, but for this project, only a force sensor is mounted.

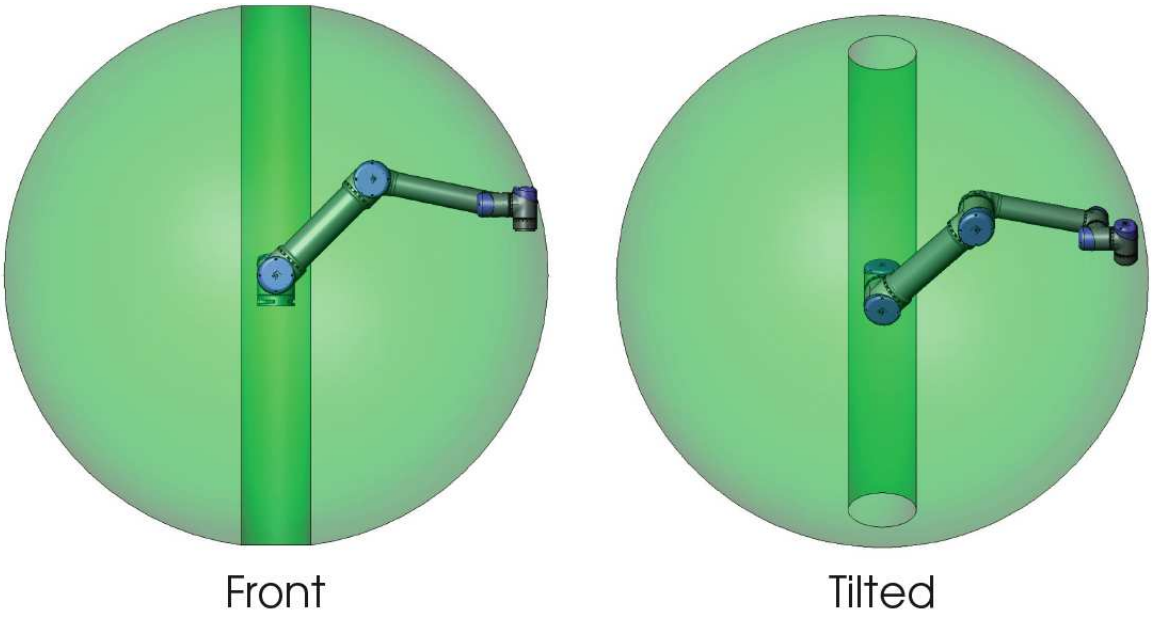


Figure 5.2: The workarea of UR-6-85-5-A

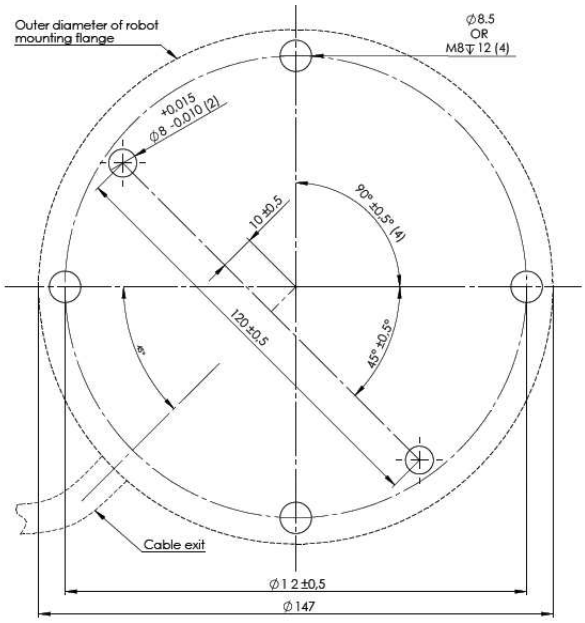


Figure 5.3: The mounting flange of UR-6-85-5-A

Chapter 6

Implementation

6.1 Analysis of Solutions

There are two different ways to approach the problem of converting the UR robot arm into a deburring tool:

- To place a grinding machine on the end effector. This would allow the robot arm to deburr big objects which fit into the arms working area.
- To place a gripper tool, like a suction cup, on the end effector, and pass the desired object through deburring tools. This solution is focused on smaller objects, since the arm can only lift up to 5 kg with precision.

A comparison of the two methods for a solution has been made in table 6.1

Each of these solutions has strengths and weaknesses, but the most important aspect aimed at in this project is precision. If a grinding mill was to be used, the force sensor would not be able to feel a steady push from the tool tip, since the mill would be shaving off pieces of the object to deburr. This would mean that the amount shaved off the object to deburr depends on the precision of movement of the robot arm and the time of displacement of the tooltip. Since neither can be assumed to be reliable, the second method is concluded to be the best solution, see figure 6.1. In short, the solution consists of a controlled-path robot behaviour, combining joint and linear interpolation along with the force feedback approach.

6.2 Method Implementation

Since this project is only a testbench, the "suction cup method" is tested, without an active suction cup, i.e. a victim element is placed on the end effector, simulating an element which is attached to the end effector through a suction cup, see fig. 6.2. Furthermore, the element

[1] In tbl. 6.1 on the following page it is assumed that the density of steel is 7.8 g/cm^3 [HDY04] and thus, the arm is capable of lifting a square plate with a thickness of 5 mm and sides of 35 cm.

Table 6.1: Method comparisons

	Tool mounted on end of robot	Workpiece mounted on end of robot
Weight of object to deburr	N/A	5 Kg
Reach of robot arm	Radius of arm	Depends on the weight and size of the object to deburr
Size of object to deburr	Must be inside the reach of the robot arm	Depends on the weight of the object[1]
Precision of deburr process	Depends on the odometry of the robot arm, since force sensor does not work effectively with a grinding mill.Therefore, low precision is assumed.	Depends on the force sensorand software code. The forcesensor permits adaptability,therefore, high precisionis assumed
Strength of material	Not necessarily soft metals like aluminium	All kind of materials as long as a gripper can be designed
Speed	Highest	Higher than most machine or hand deburring processes

holders will not be built, but it is assummed that all elements are picked up at the exactly same position with the same rotation.

For the proof of concept, it is assumed that the robot is standing in a production line where it has to deburr metal plates with the dimensions 10 cm × 15 cm Figure 6.3 shows a flowchart of how the robot deburrs all four sides of the elements. An element has been mounted on the existing tool of the robot from the project [OI09]. The idea behind this setup is to simulate a deburring process of four sides of this element in a model of a setup around the robot. For this setup a model has been drawn for a deburring platform, see appendix E on page 62. With help from the AUT department, this model was made in wood and mounted within the workspace of the robot. The model was mounted on a small table next to the robot in the lab, with clamps to prevent it from moving when the robot pushes the victim element against it. The robot was programmed to simulate the process of picking up the element, deburring its four sides, and then delivering the element for further work elsewhere. The programming for this task will be discussed in chapter 7 on page 32. The tool chosen to be simulated is like the one in figure 4.1(b). The size of the tool is determined depending on the size of the element, which in this case is 10 cm × 15 cm, but the size of the tool can easily be changed if the size of the workpiece should be changed. It

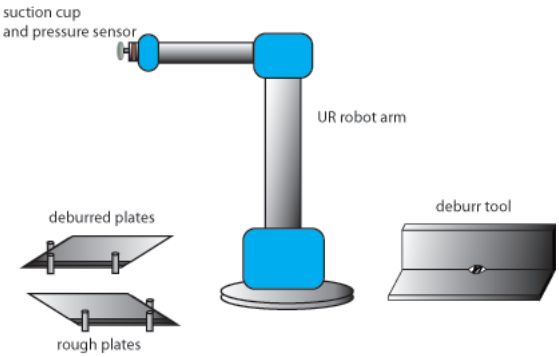


Figure 6.1: A simplified model of the theoretical setup of the deburring process

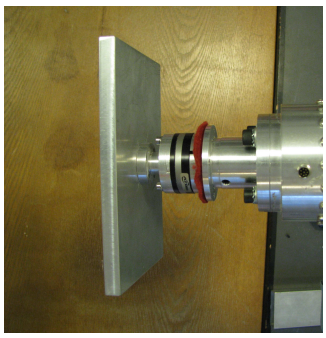


Figure 6.2: Test bench setup with an element attached to the robot tooltip

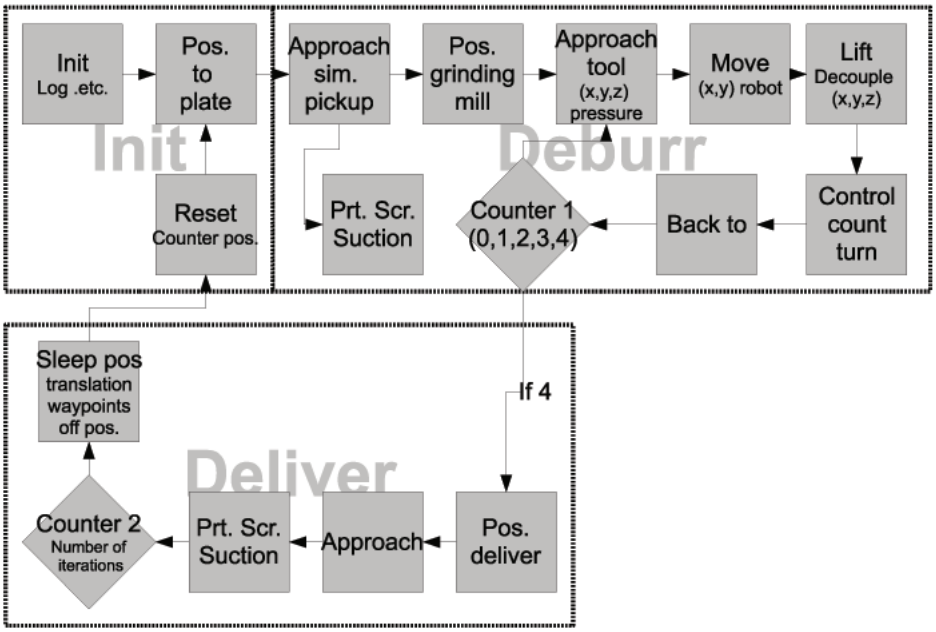


Figure 6.3: A flow chart of the deburring process

should be kept in mind that the size and speed of the cylinder doing the deburring depends on which material it should work on, how much material it should remove and how fine the result should be.

Appendix D on page 60 also shows a sketch of the victim element mounted on the robot. The mounting between the element, sensor and the robot is not included, since it was already made before this project started. The element ends up being mounted approximately 10 cm from the center of the tool tip[2] of the robot.

6.2.1 Deburr Process

The movements, before and after the element is near the deburring machine, are easy to program as point to point movements. This also includes the rotation of the victim element to change side for deburring, and the position before the deburr process is started. While the robot is to collect or deliver an element, the force sensor is used to make sure that the robot is pushed against the element or the element underneath before a vacuum is activated or deactivated if a suction cup was implemented.

The elements ready to be picked up by the robot are to be placed in a holder where the elements are fixed in a precise position. In this way, the robot always picks up an element in almost the same position. Due to programming, a small deviation of ± 1 mm in this position is allowed. The position of the holder for unloading the plates does not have to be in a fixed position either. The holder is allowed to deviate in both rotation and position by $\pm$ 1 mm.

In the position for deburring, no matter which side of the element is chosen for deburring, force measurements must be used for impact control and regulation. First, impact control must be used to make the element move all the way to touch the deburring tool in two directions. The robot is programmed to move towards the deburring tool in one direction, the Z_s-direction of the force sensor, see fig. 6.4. This corresponds to a continous movement along the X_r-axis and $-Z_r$-axis of the robot, until the force sensor measures a given reference value.

To complete the positioning of the element before the actual deburring is done, contact has to be made with the rest of the sled of the deburring setup. This is completed by moving the plate a 5 mm away from the machine and approaching the sled in the force sensor's $-X_s$-direction, which correspond to the $-X_r$-direction and $-Z_r$-direction of the robot, until a force reference value is reached once more. Then the approach in the force sensor's Z_s-direction is called once more to make the plate reach the sled as close as possible.

Fixed in the sled, the element is ready to be run by the deburring mill, which means the element is moved along the robots Y_r-axis, while it is pushed against the tool sled in the force sensor's Z_s- and X_s-direction. The movement is controlled by a PI-regulator trying to maintain a constant force in the Z_s-direction. Position regulation along the X_r and Z_r axes is desired, and two PI-regulators maintain the wanted position along these two axes.

When one side has been deburred, the robot deburrs three more sides before it is done

[2]TCP, Tool Center Point, named by UR

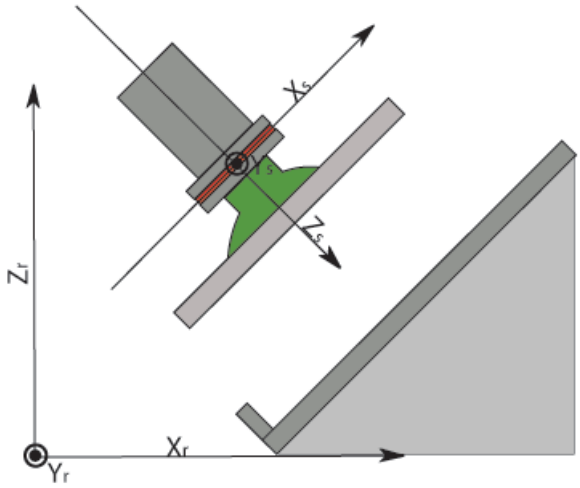


Figure 6.4: Model of approach to deburr tool. The Y_r and Y_s axis are chosen according to the right hand rule. A spindle is

and ready to drop off the victim element again. In a production line, the element would be turned upside down at the drop off point and put trough the process once more to deburr all eight edges, but this is outside of both our time line and main problem, and will therefore be saved for future work.

6.2.2 Linear control design and kinematic values

The regulation used for the project was based on the hybrid-control used in [OI09]. Fig. 6.5 shows a general block diagram of how the desired regulation is achieved. The ideal solution for the deburring process would have force regulation between the victim element and the deburr platform on the robot's X_r and Z_r axes, see fig6.4.

The resulting system to be regulated would be of the multiple-input/multiple-output (MIMO) kind. This fact, paired up with torques and forces generated on the force sensor due to torsion when the victim element is not exactly aligned with the deburring sledge, results in the need of complicated regulation. The needed regulation is taught at DTU as part of a masters course, and due to limitations on time, a simpler solution is chosen. The regulation solution will have the following properties:

- Force feedback and regulation in the robot's x- and z-axis
- Position feedback and regulation in the robot's y- and z-axis
- A hybrid force/position regulation scheme
- A slightly underdamped system, which gives a better result

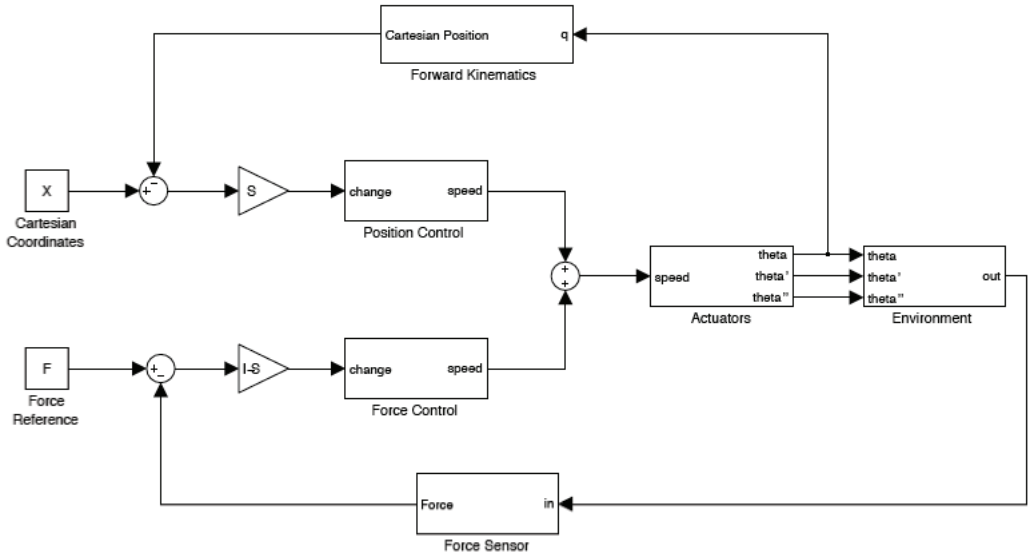


Figure 6.5: Block model of a hybrid force/position control scheme from [OI09]. Note that the forward kinematics are used to transform the joint positions θ_i to Cartesian coordinates, which are used as feedback for the position controller.

This regulation was achieved in the draw function of the python code, see chapter 7 on page 32 for more information. The tuning of the values K_p and K_i was made by hand, trying different values, although the initial values were found using the Ziegler-Nichols criteria, as described in [OI09].

The values for the Denavit-Hartenberg notation used are shown in table 6.2 The values are then inserted into the homogenous transform as stated in chapter 4.2 on page 15, and using eq. (4.4) the homegenous transform ${}_0\underline{\underline{T}}_6$, which will be used in the programming for movement and location of the robot.

Table 6.2: Denavit-Hartenberg values used for the robot. They are obtained through measurements made on the robot arm

i(frame)	$\alpha_i - 1$ [°]	$a_i - 1$ [m]	d_i [m]	θ_i
1	0	0	0.0892	θ_1
2	90	0	0.1357	θ_2
3	0	-0.42500	-0.1357	θ_3
4	0	-0.39243	0.1090	θ_4
5	90	0	0.0930	θ_5
6	-90	0	0.0820	θ_6

Chapter 7

Programming the robot

7.1 Functions and their uses

The code for this project builds upon the program from an earlier project, [OI09]. After an analysis of this code, functions which were needed to complete the task had to be written or modified. Afterwards, all the functions which were no longer in use had to be erased. The purpose of the new functions are described on the flowchart in figure 6.3 on page 27.

These functions created with Python work as a high level programming language working on top the URScript. There are two classes which were made:

- The force class, containing functions designed to retrieve information and remove bias from the force sensor F.0.3
- The connection class, containing functions designed to speak with the robot, and thus send all movement scripts to the robot F.0.2

These two classes each have their own file, and a third file, called maindeburr.py F.0.1, serves as a primitive GUI. These three files can be seen in Appendix F, and can be analyzed if a detailed understanding of the different classes and functions is desired.

Mainly five kinds of tasks need to be scripted in order to do the deburring work:

Large movements in workspace These movements are made by establishing waypoints where the robot arm has to stop. These points are called through the *movej* command[1]

Approach with sensor feedback These functions were made by having loops moving the tooltip in a desired direction, with the *speedl* script, while comparing the data of the force sensor to a given reference value. In most cases this reference value was 4 N. This kind of function is also used to simulate the pickup and delivering of the elements to be deburred

[1]For specific details on the working of these commands, refer to URscript Manual [Robb]

Decoupling movements These movements are made with the *speedl* script, moving only short distances away from the deburr setup. The original script was made by Ingólfsson and Gudlaugsson, but this function is now divided into two different scripts, decoupling on different axes

Rotation of the tool point This is achieved by logging the current position of the joints and then using the *movej* script to rotate wrist 3 of the robot. The rotation is made with a slight bias due to the general position of the robot arm relative to the setup

Translation of the tool point with force regulation activated This is the most important movement of the project, since it is the one that defines the precission of the deburr work. This movement was achieved by creating a path, as described in chapter 4.2.2, and continously sending the information from the force sensor and the position feedback through the PI-regulators. This was done in the *draw* function of the *connection* class. The position feedback uses the forward kinematics in order to find the Cartesian coordinates from the data received by the robot.

Since the victim element at the tool point creates a force bias due to gravity, the force sensors bias needs to be removed after most of the movements are completed. This function is defined in the force class.

Some of the used functions were already written by Ingolfsson and Gudlaugsson. But many of them are partially or completely rewritten in order to fit into this project, e.g. the original approach function only moved in the Z_s direction, parallel to the X_r-axis, while the rewritten one moves in a combination of X_r and Z_r axes. The source code has been commented in order to make clear which functions are based on Ingólfsson et. al. original functions.

Two python-modules are loaded into the program: *numpy* and *socket*. Numpy, or numerical python, is in charge of the mathematics and creating different matrices. Socket is in charge of TCP communication with the robot controller, and adding this module allows to functions like *socket.rcv* and *socket.send* to be called. It is mainly due to the capabilities of this module that python was chosen as the programming language by Ingolfsson and Gudlaugsson.

7.2 User manual for the program

To start up the program, it should first by assured that the robot, user-pc and sensor-pc are connected and are on the same network.

The IP-settings for the robot should be: IP:192.38.66.237 Subnet: 255.255.255.0, the IP-settings for the user-pc should be: IP:192.38.66.x[2] Subnet: 255.255.255.0, and the IP-settings for the sensor-pc should be: IP:192.38.66.252 Subnet: 255.255.255.0. Control the connection between the sensor and the sensor pc is plugged in correctly.

[2]x should be a number between 1-255, except 252 and 237

Then the Visual Basic 6 script written for [OI09] on the sensor PC should be started, press the following buttons: Listen, Initialize sensor, Remove bias, and Fetch data. The last one is to check that everything is working, and if the data is not close to zero it might suggest an error.

Turn on the robot, follow the text on the screen to initialize it. Remove anything withing 20 cm of the robot arm before turning the power on and be careful not to hit anything while moving the arm, during this stage.

When the robot is initialized, choose "Program Robot" on the main screen and go to the Log tab. This will help understanding any problem, if one should occur. Make sure the Ethernet controller does not have packet loss at this stage, otherwise restart the robot right away. Now it is possible to start the user interface at the user-pc. Make sure that the user-pc has Python version 2.5 and the source code from this project. Start the file called maindeburr.py from Appendix F.0.1, on Microsoft Windows 2000 or newer. This can be done by a double click on the file or by running the file in a command window. In Unix/Linux systems it can be run in a terminal window.

The program will start moving the robot to the first position and when it is done, the main screen will show, see figure 7.1. The following choices are possible:

deburr Choosing this will make it possible for the user to choose how many elements to deburr and then start the process. The maximum number of elements is 10 pieces.

debug Choosing this will make it possible for an advanced user to access the temporary menu, used to do the programming. This menu is partly a copy of the one use by [OI09] with a few extra options

exit Choosing this will shut down the program, after closing any open files or sockets

Welcome to
the deburr program
The commands for this program are:
deburr = Start deburring
debug = Enter debug menu
exit = Exit the program
If no or a wrong input is given
you will return to this screen
Command:

Figure 7.1: Mainscreen for the user interface at the user pc connected to the robot controller and sensor pc

Before any use of the robot always read the safety instruction in the user manual for the robot [Roba].

Chapter 8

Calibration and Test

This chapter shows how the solution for the given problem was tested and how the instruments were calibrated in order to get precise and accurate measurements. Further, the collected graphs and data, are discussed and compared.

8.1 Test of communication speed

Ingólfsson and Gudlaugsson observed that communication over Ethernet between the control PC, sensor PC and the robot not always worked as described in the data sheet of the robot. The sensor PC did not show problems of communication, due to the fact that it does not communicate with the robot, but only with the sensor and the control PC. A model of the network can be seen in figure 8.1.

In the script manual [Robb] of the robot it is stated that the robots real time RuntimeMachine[1] can handle communication at a speed of 125 Hz. This frequency has proven to be difficult to mantain while running communication over Ethernet. The robot crashed with the error "No Controller"[2] and stopped if calls were sent at this rate. By restricting the send rate to 41 Hz, the crash error was prevented from occurring everytime. This crash error still appears sporadically, without any clear reason.

To test the controller crash problem, a small piece of code was designed to call one of the UR Script commands at a determined rate. This also gave an opportunity to learn move about the UR Script. The *random()* command was chosen, because the robot does not have to move for this command to work and thereby does not have to ensure that it always stays inside its own workspace. This command is also supposed to return a value to the control PC, like most of all other commands that move the robot.

This small program consist of a "while" loop, where the speed of the loop can be controlled to determine the frequency of the call of the *socket.send()* command. The idea was then to run the loop at different frequencies and see how long it would run without

[1] See chapter 5.2 on page 22

[2] In the log: PolyScope disconnected from Controller

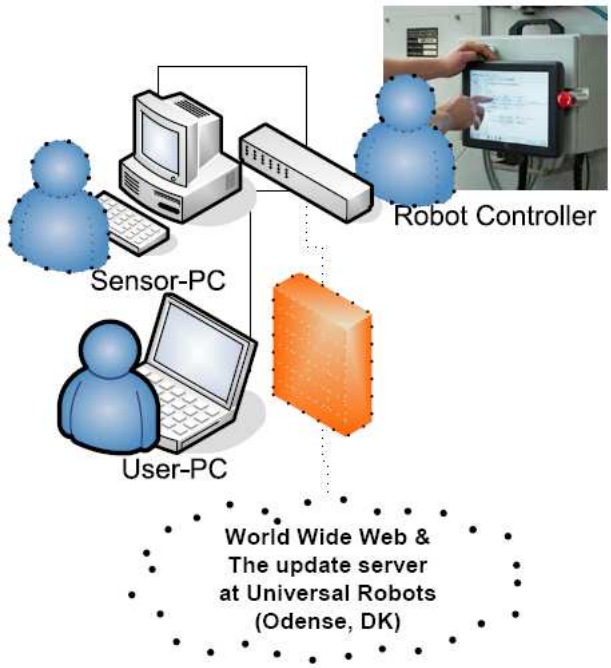


Figure 8.1: A model of the network around the robot

getting the error on the touchscreen of the robot. To determine if this command actually reached the robot and the robot answered, a program was included in the loop, which wrote the answer from the robot with a time stamp to a file. This file did work, but the answer from the robot was not as expected, since it consisted of the position of the robot and not a random number from 0-1 as the UR Script manual stated. Also, the time stamp to control the frequency in the text file was not working as planed and needed reprogramming to be sure it was accurate.

Due to the failure of completion of this test, the project was continued with restrictions on the communication speed. This means that when a movement is done which depends on a read-out from the force sensor, the frequency for every *socket.send()* command call to the robot is locked to 41 Hz, as in [OI09].

The only function not having the same frequency restriction is the *approach_z_x*, which has even more strict limitations on the speed of the *socket.send()* calls.

8.2 Force feedback during deburr

The read-out of the force sensor was logged for analysis purposes and can be seen in fig. 8.2.

From this graph, it is clear that regulation toward a force reference of 4 N is achieved. The graph shows the force feedback each time a side of an element is passed through the deburr setup. It is also quite clear here, that the force regulation is very sensitive

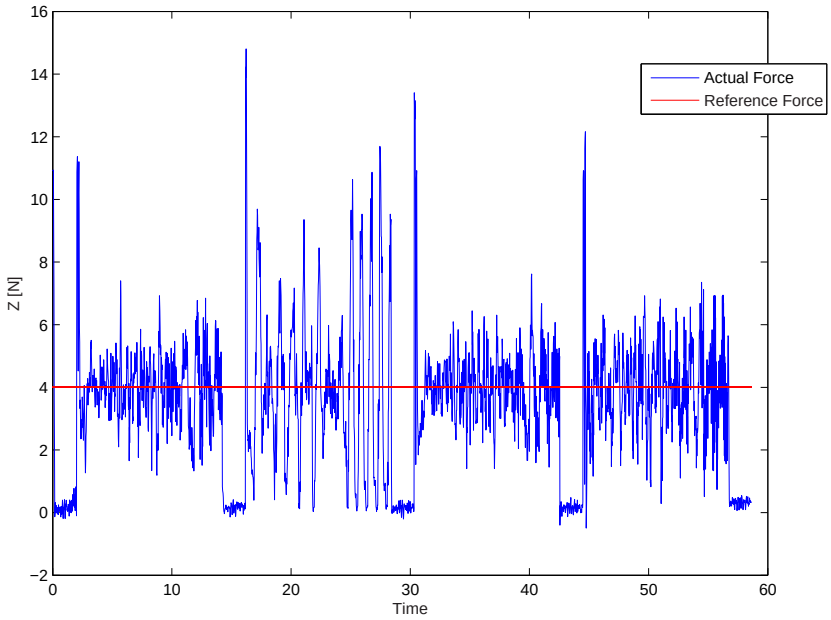


Figure 8.2: Force feedback during the deburring of the four sides of an element. The first, third and fourth deburr maintain a stable pressure agains the deburr sledge

to the start position of the robot, and whether the victim element is completely aligned with the debur sledge or not. The first, third and fourth runs maintain an even force regulation, while the second loses its grip against the deburr sledge. This happens because the alignment angle between the sledge and element is too big when the element is rotated into the second position for deburring. This could be solved by having a tool tip which is able to bend and adapt a few degrees, so the plate ends up being completely flat against the deburr sledge.

8.3 Noise on the force sensor

The force sensor used in this project has been described in chapter 5.1 on page 21 and it has been noted that it had an unpredictable error, which showed as a a peak read-out of a force larger than what the sensor should be able to measure. In the Appendix A on page 46 sets of data are listed, containing information read out from the force sensor in nine different positions in the workspace of the robot:

- Random position
- Deburr positions $1-4$, just before the robot starts moving towards the deburr setup
- Initialize position
- Stretched out horizontal, with the tool at maximum reach, downward, and upward

In each data set there are values which are out of the measuring range of the force sensor. It should be noted that the sensor cannot measure more than ±40 N of force in the x-axis and y-axis, and ±120 N of force in the z-axis, see table 5.1 on page 22. The data received reaches numbers up to ±255 N or even $\pm 256 \cdot 10^8$ N, and this error is not connected to only one axis.

These peak errors have to be removed from the data sent to the system, otherwise the corrections for the robots movements can be fatal for the equipment and setup. Still, the setup has completed the deburr process of 10 elements in a row without crashing or having serious errors.

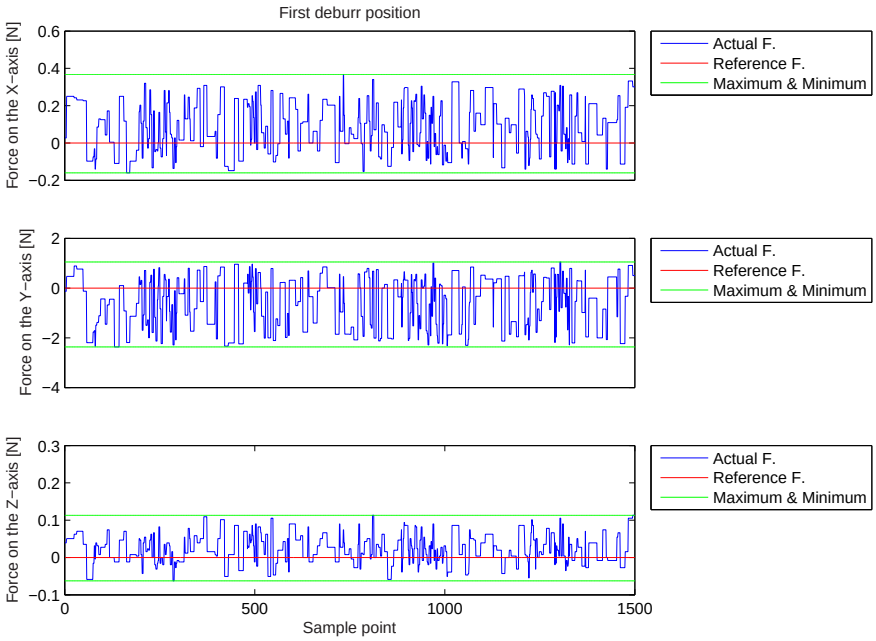


Figure 8.3: Graphic representation of noise recieved on the force sensor, when the robot is in the first deburr position, see also Appendix A

With the high peak errors removed from the data sets, the force sensor still experiences errors, but smaller than ±2 N. This can be seen in figure 8.3. The figure show force measurements from all three axis at the moment where the robot is at a waypoint, just before it starts deburring the first edge of an elelement.

If these numbers are compared to the rest of the measurements in the Appendix A it is apparent that the force sensing depends on when exactly the force bias is removed from all three axis. It is concluded that the measured noise comes from the robot. While standing still in a position in space and turned on, the robot will always vibrate a little and this movement is measured by the force sensor. The vibrations come from the motors in the robot, which are trying to hold the robot still in the preprogrammed position while working against gravity. The hight vibration measurements are due to the weight of the element at the tool tip, which amplifies the error readings at the sensor.

When the robot moves there is also noise on the sensor, but this phenomenon has not been analyzed in this project. When the force sensor is used throughout this project, the noise coming from the vibrations of the robot has been discarded as always being within a margin of ±4N during a move through the deburr tool. This can be seen in section 8.2 on page 36. During the project, this noise has been taken into account regarding the linear control, which led to the use of a PI-regulator instead of a PID-regulator[3].

In [OI09] noise problems were minimal due to the small weight of the tool on the tip of the sensor. This noise was not taken into account since most of the noise came from the contact point between the chalk and the surface of the chalkboard or between the peg and the block of tree with a hole.

[3]See chapter 4.4 on page 19

Chapter 9

Errors in the robot

The robot used in this project is a prototype model used for tests inside UR. This means, it was built as one of the first of its type and some parts of the robot and its controls may have changed in newer version. This section will explain some of the problems which were encountered throughout this project.

When the robot is being turned on for the first time after long period of inactivity, it does not always work and needs to be restarted. The error consists in some kind of failure in the Ethernet card or driver, which does not start up the Ethernet properly. The log states "Ethernet 001 Packets loss", which does not explain much, but implies that the error lies in the network communication drivers of the robot.

Another error comes after the control box for the robot has been moved. The wires for the touchscreen might be moved as well and an error occurs with the touchscreen, making it impossible to control the robot without an external mouse or keyboard. This error has not been present all the time, but appears due to wear and tear on the wires which go into the control box. When these wires were installed at UR, nothing was used to prevent the sharp edges of the control box to cut into the wires, and if a closer look is taken, it is now possible to see through most of the isolation cap and into the cores or shields of almost all the wires.

This model was not meant to be transported, moved or placed in an environment which vibrates in any way. This limitation has not been commented to the AUT group, or any student working with the robot. The limitation became apparent when the log suddenly one morning simply stated "48 V Internal power supply is at 0V" at start up. The robot had the day before shown no problems when turned off. Universal Robots was contacted and the problem was explained. The solution was that the control box should be taken apart an examined at DTU, rather than sending it to Odense and back, which could have taken weeks off the projects time schedule.

When taken apart, it was clear what was wrong: one wire from the 48 V Internal power supply had been torn out from its socket on the main controller board. This apparently happened due to the length of the wire and vibrations between the power supply and the main controller board. While the controller was taken apart it was also noted that two out of three ceramic resistors had almost broken completely off. This also occurred due to

vibrations, and because the resistors had not been mounted correctly, but had only been installed in a socket in one end. The weight of each resistor had then been enough to move it around every time the controller box was shaken or moved due to gravity. After some time, the wires connecting the resistances must have become weak and broken off.

Representative of UR stated that the resistors are used to burn off energy when the robot is deaccelerating and no damage should have been done as long as the robot had not been used intensively over a long period. Two new resistors were sent from Odense and installed upon arrival, this time secured by strips to avoid the same error again later on. UR claims that this construction error has now been corrected.

In section 8.1 on page 35 an error concerning the controller crashing has been explained. During the project, this error has appeared on different occasions, and was mentioned to UR. It was discussed if the heat that building up inside the controller box could affect the controllor. UR insisted that is was not the case, because the temperature should not rise above the maximum working temperature for all the components inside the controller box.

Chapter 10

Conclusion

Throughout the realization of this project, several branches of engineering and tools have been used. Programming, linear control, physics and mathematics are among the most prominent, and they were all used together to achieve a result. This result is the creation of a test bench which proves that a robot arm UR-6-85-5-A is able to deburr four sides of a metal plate (victim element) using a force sensor installed on its tool tip. A setup was created to simulate the deburring process, which is divided into the following steps:

1. The user chooses how many elements are to be deburred
2. The robot arm simulates picking up an element with a suction cup
3. Using force regulation in order to follow a surface, the robot passes the victim elements four sides by a mock-up of a deburring machine
4. The robot arm simulates delivering the deburred plate at a given position
5. The robot repeats the procedure if necessary

Programming was made with the Python language, and proved to be very effective to the task. It eased the use of the URScript language and communication with the robot arm. Force regulaton was achieved through the use of a PI-regulator acting in the software. It regulated along the Z-axis of the sensor, and proved to be moderately adequate for the task. Other control techniques might have been better for force regulation in two axes, but knowledge of those techniques was outside the scope of this project.
The solution is not as precise as it was hoped it could be. This stems from the fact that only force regulation in one axis was achieved. At the same time, a solution was expected to be found for removing/dampening the vibrations generated by the robot, but they only became worse due to the heavy weight on the tool tip.
The team is satisfied with the knowledge acquired during this project, and with the results achieved.

Chapter 11

Future Work

Throughout this project, more problems have been revealed during the search for solutions to the stated questions in the problem statement. Some of these have been outside the frame of this project, others were too time consuming, and some have had to be discarded due to the lack of the knowledge needed to solve the problem.

The following points are tasks or problems which could be solved in the future as a special course, or simply for the challenge:

Change in size of the elements to be deburred The product of this project can be made to take an input of the dimensions of the victim elements and thereby adjust all the waypoints in the procedure to take the dimensions into account before moving from waypoint to waypoint

Improving the use of the deburr tools As described in 4.1 on page 9 the wear and tear on the deburr tool will make the deburring less precise for every run, and at some point the tool needs to be sharpened or replaced. When a tool has been chosen, the amount runs before the tool needs to be changed has to be determined, if the tool manufacturer has not stated this already. A solution to extend the life of a tool can be to made through a mechanism that moves the angle of attack on the tool between or during each run

Deburring all eight sides of an element Another future feature can be to design a regrip fixture for the setup inorder to make the robot capable of deburring all eight edges of a victim element

Expansion of the control to force feedback in several axes The SISO system developed in this project can be optimized into a multiple input/multiple out (MIMO) system that is able to use force feedback from all axes of the sensor or even the torque outputs. This would make the victim elements follow all the sides of the modelled deburr tool even smoother

Noise reduction A filtering system can be built inorder to remove even more noise from the force sensor at the TCP of the robot. This would make the controlled movements

even smoother

Completion of test setup The setup can be completed adding a suction cup at the tool tip and a vacuum system mounted near the robot. Also the holders beside the robot for the arriving and leaving victim elements can be designed and put into the setup. A real grinding mill could be installed too, although some security measure should be established

Bibliography

[A.] ATI I. A. Mini40-r. On-line, http://www.ati-ia.com/products/ft/ft_models.aspx?id=Mini40.

[Cra04] John J. Craig. *Introduction to Robotics - Mechanics and Control*. Prentice Hall, 3rd edition, 2004.

[CW76] Raymond F. Veilleux Charles Wick. *Tool and Manufacturing Engineers Handbook: Materials, Finishing, and Coating*, volume III, chapter 16. McGraw-Hill Book Co., 1976.

[Eis99] Jens Eising. *Lineaer Algebra*. Institut for Matematik, DTU, 1999.

[Gil99] LaRoux K. Gillespie. *Deburring and edge finishing handbook*. Asme Books, 1999.

[Har] Tom Harris. How robots work. *How Stuff Works*. On-line, http://science.howstuffworks.com/robot2.htm.

[HDY04] Roger A. Freedman Hugh D. Young. *University Physics with Modern Physics*, chapter 14, page 516. Pearson Addison Wesley, 11 edition, 2004.

[Iso05] James Isom. A brieg history of robotics. On-line, http://robotics.megagiant.com/history.html, 2002-2005.

[MWS05] Mathukumalli Vidyasagar Mark W. Spong, Seth Hutchinson. *Robot Modeling and Control*, chapter 3, page 496. Wiley, 2005.

[OI09] Einir Gudlaugsson Örn Ingólfsson. Flexible control of a robot arm using sensor feedback. Master's thesis, DTU Electrical Engineering, July 2009.

[OJ06] Paul Haase Soerensen Ole Jannerup. *Reguleringsteknik*. Polyteknisk Forlag, 4th edition, 2006.

[Roba] Universal Robots. *UR-6-85-5-A Users Manual*. Universal Robots, On-line (PDF), http://www.universal-robots.com/, 1.1 edition.

[Robb] Universal Robots. *The URScript Programming Language*. Universal Robots, On-line (PDF),www.universal-robots.com.

Appendix A

Force error on the axes

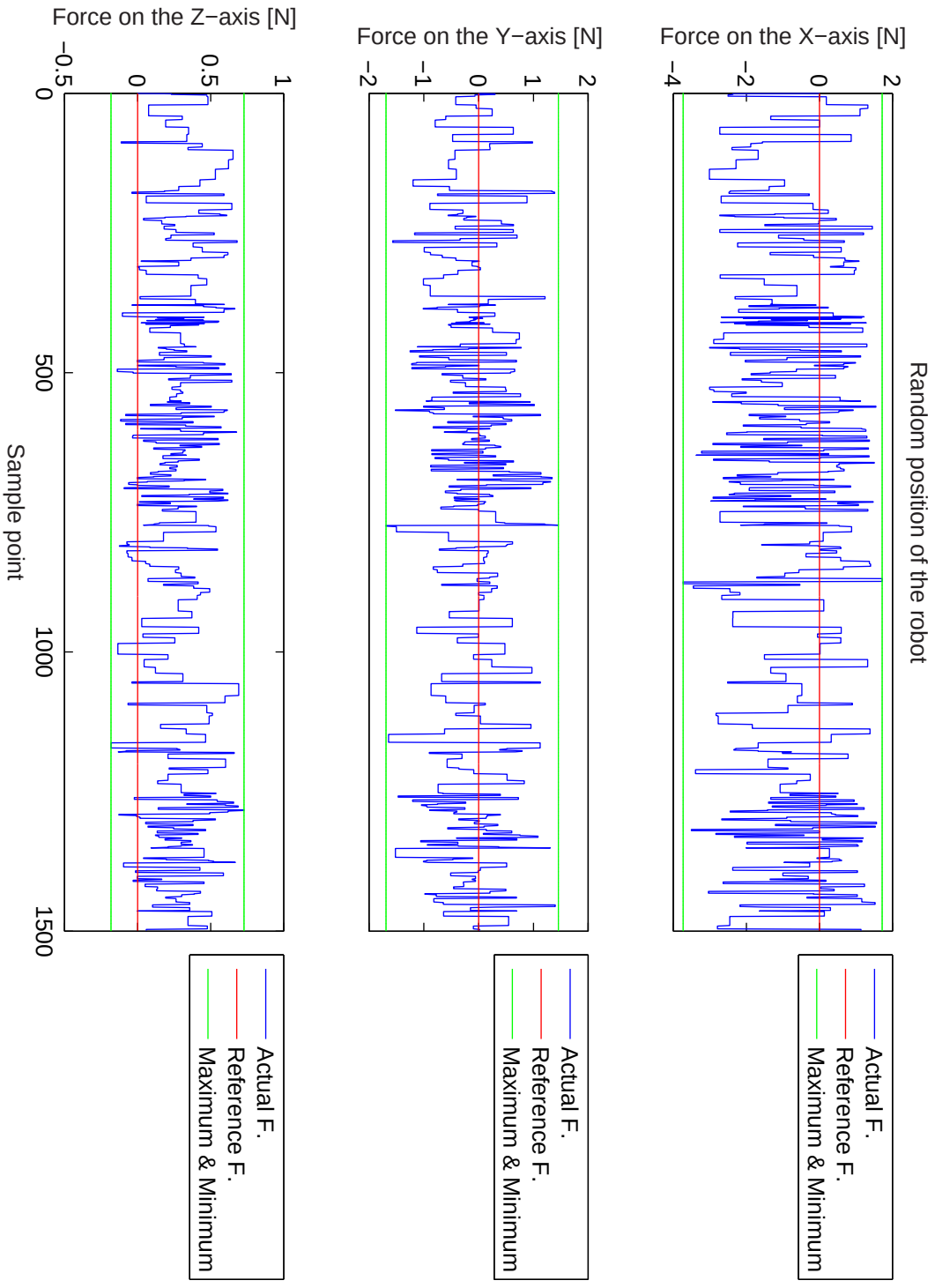


Figure A.1: Graphic representation of noise received on the force sensor, when the robot is in a random position

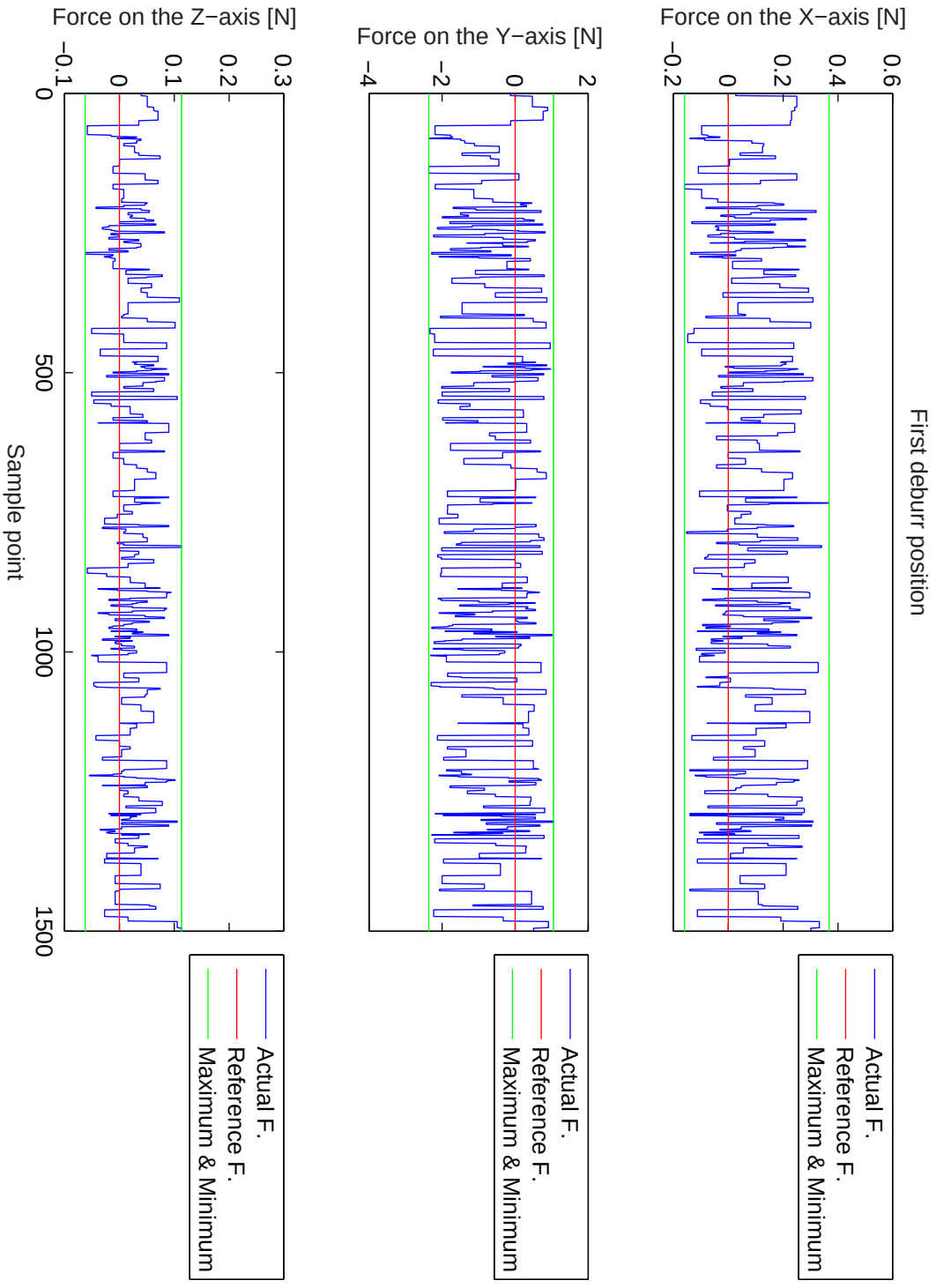


Figure A.2: Graphic representation of noise received on the force sensor, when the robot is in the first deburr position

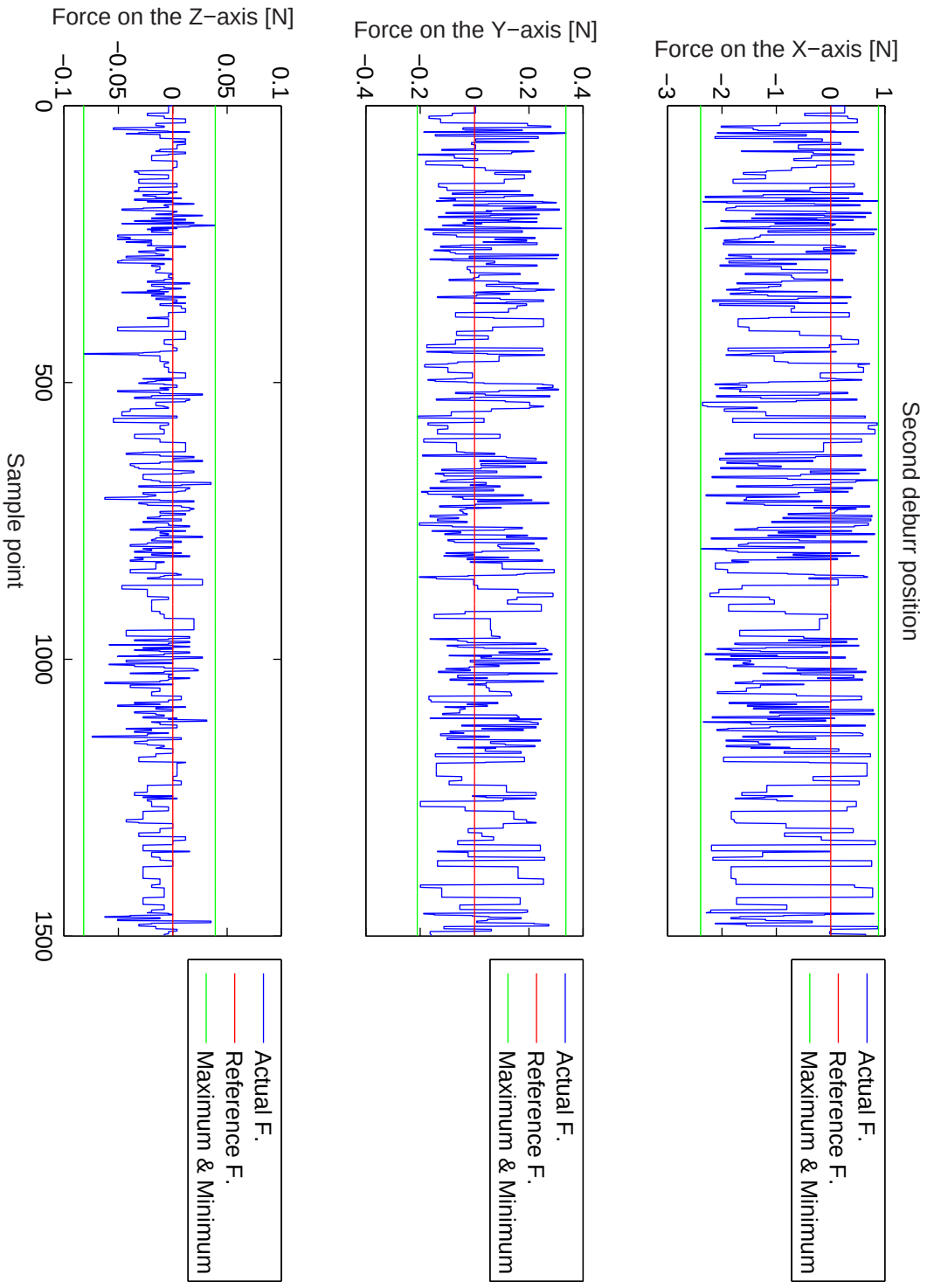


Figure A.3: Graphic representation of noise received on the force sensor, when the robot is the second deburr position

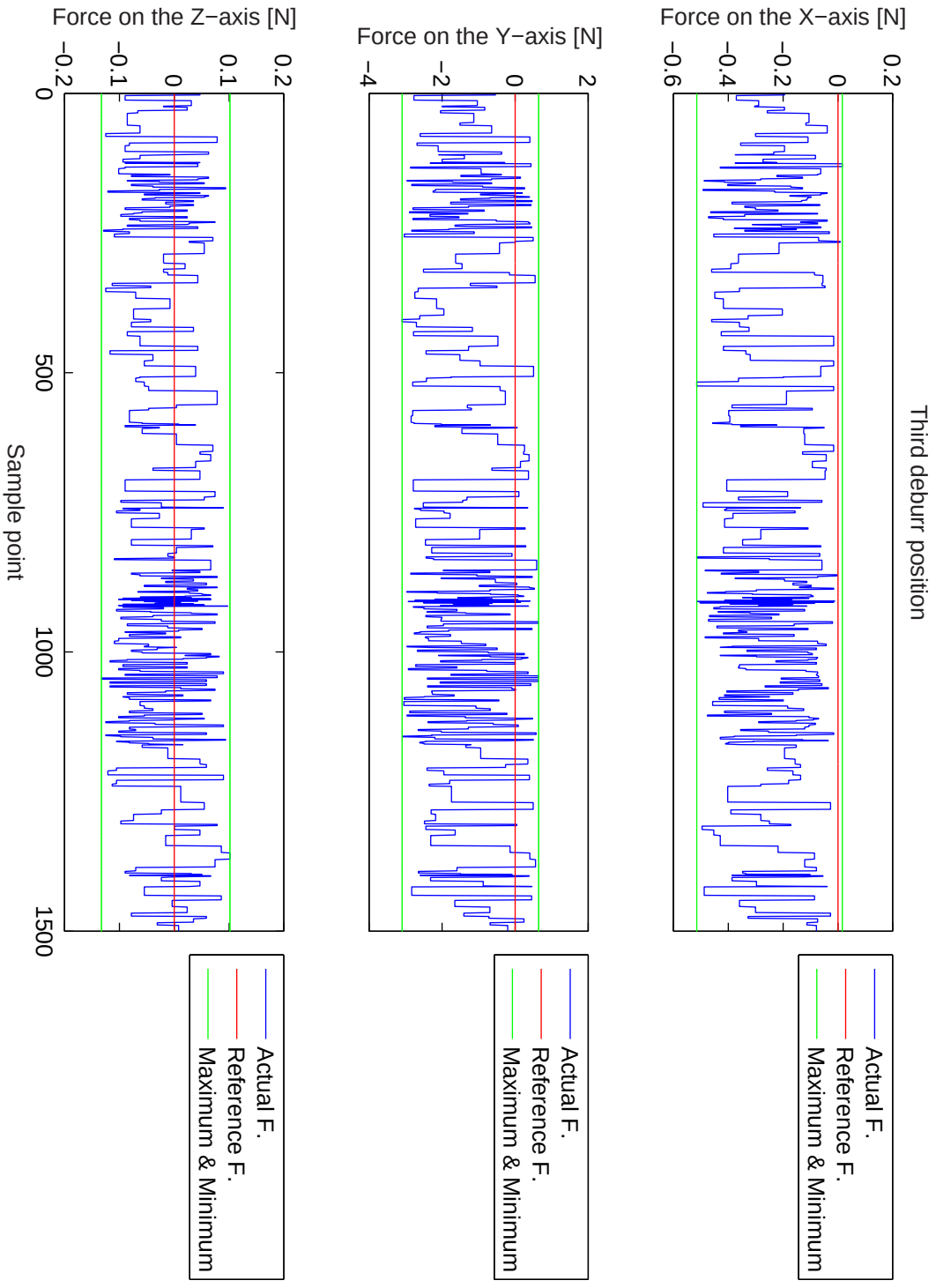


Figure A.4: Graphic representation of noise received on the force sensor, when the robot is in the third deburr position

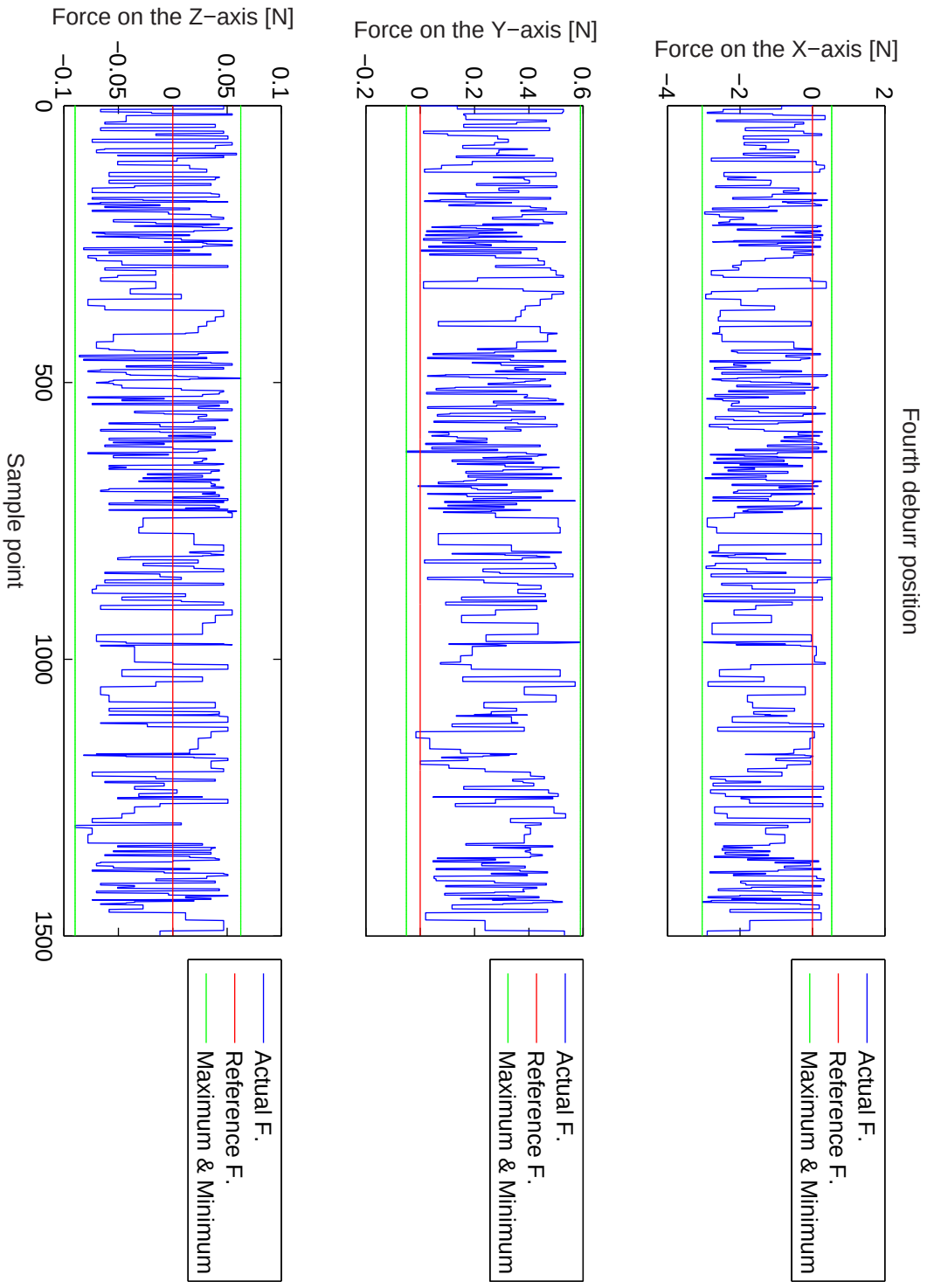


Figure A.5: Graphic representation of noise received on the force sensor, when the robot is in the fourth deburr position

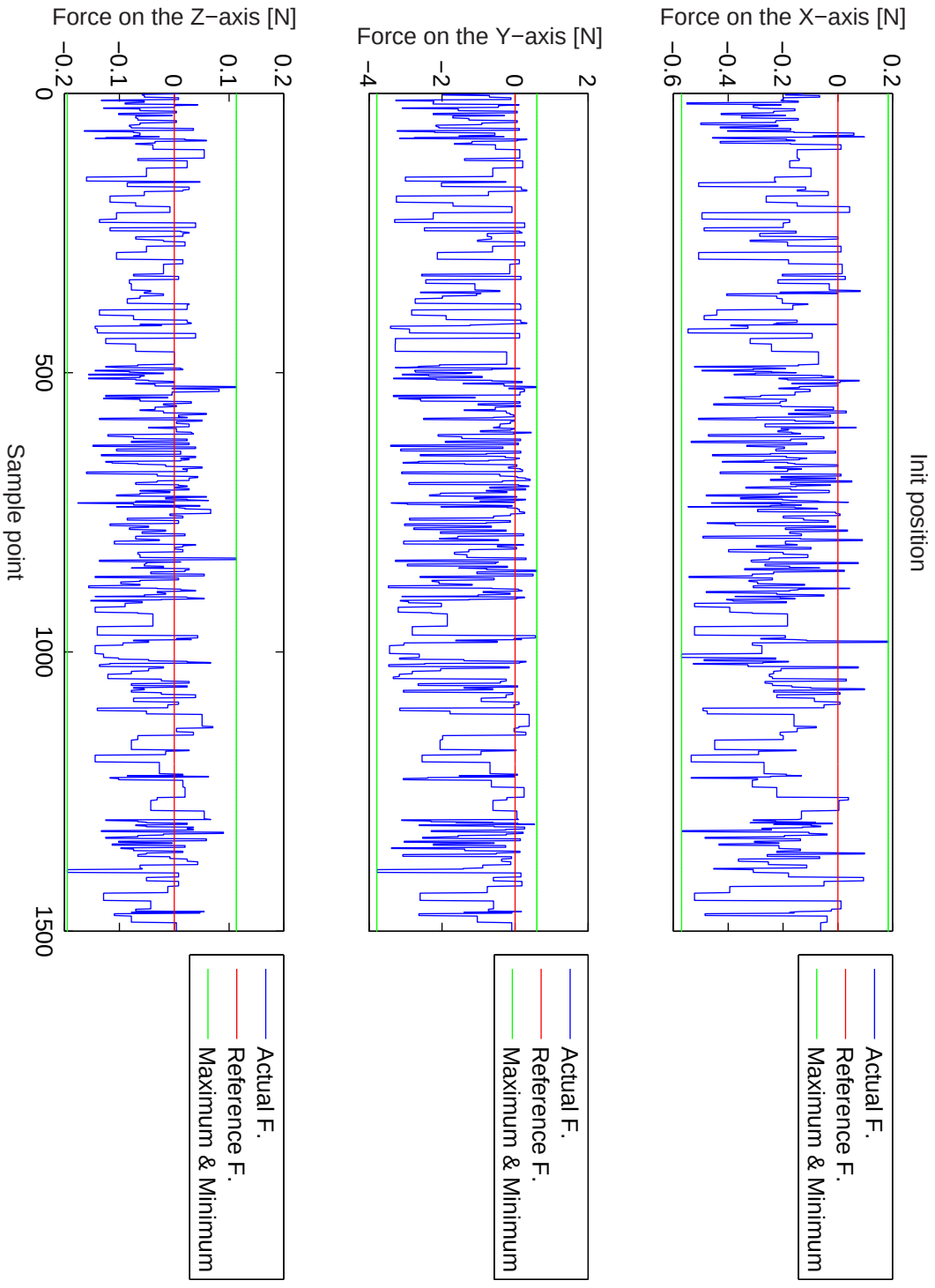


Figure A.6: Graphic representation of noise received on the force sensor, when the robot is in the initialize position

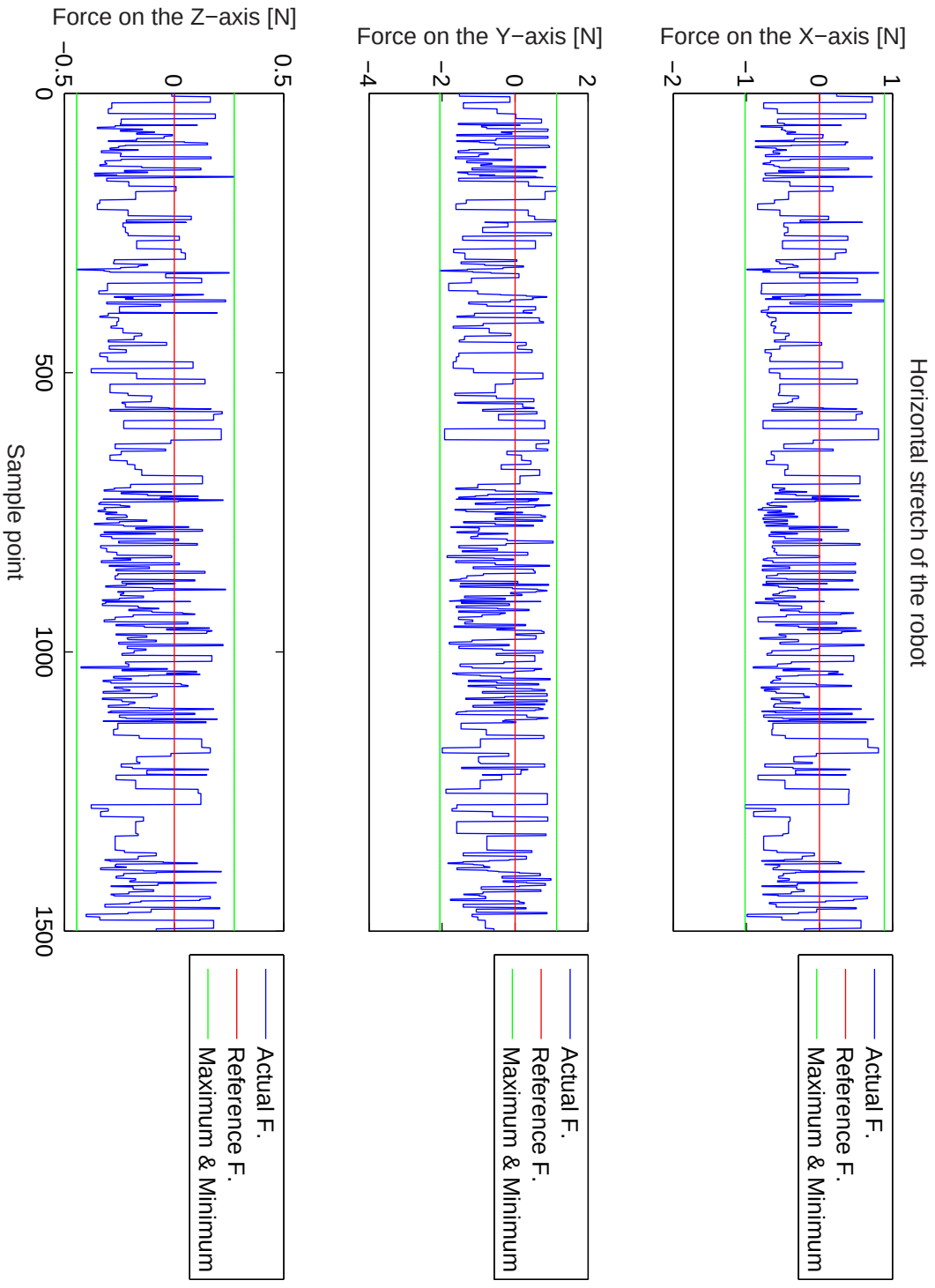


Figure A.7: Graphic representation of noise received on the force sensor, when the robot is in a horizontal stretched position with the tool pointing outward

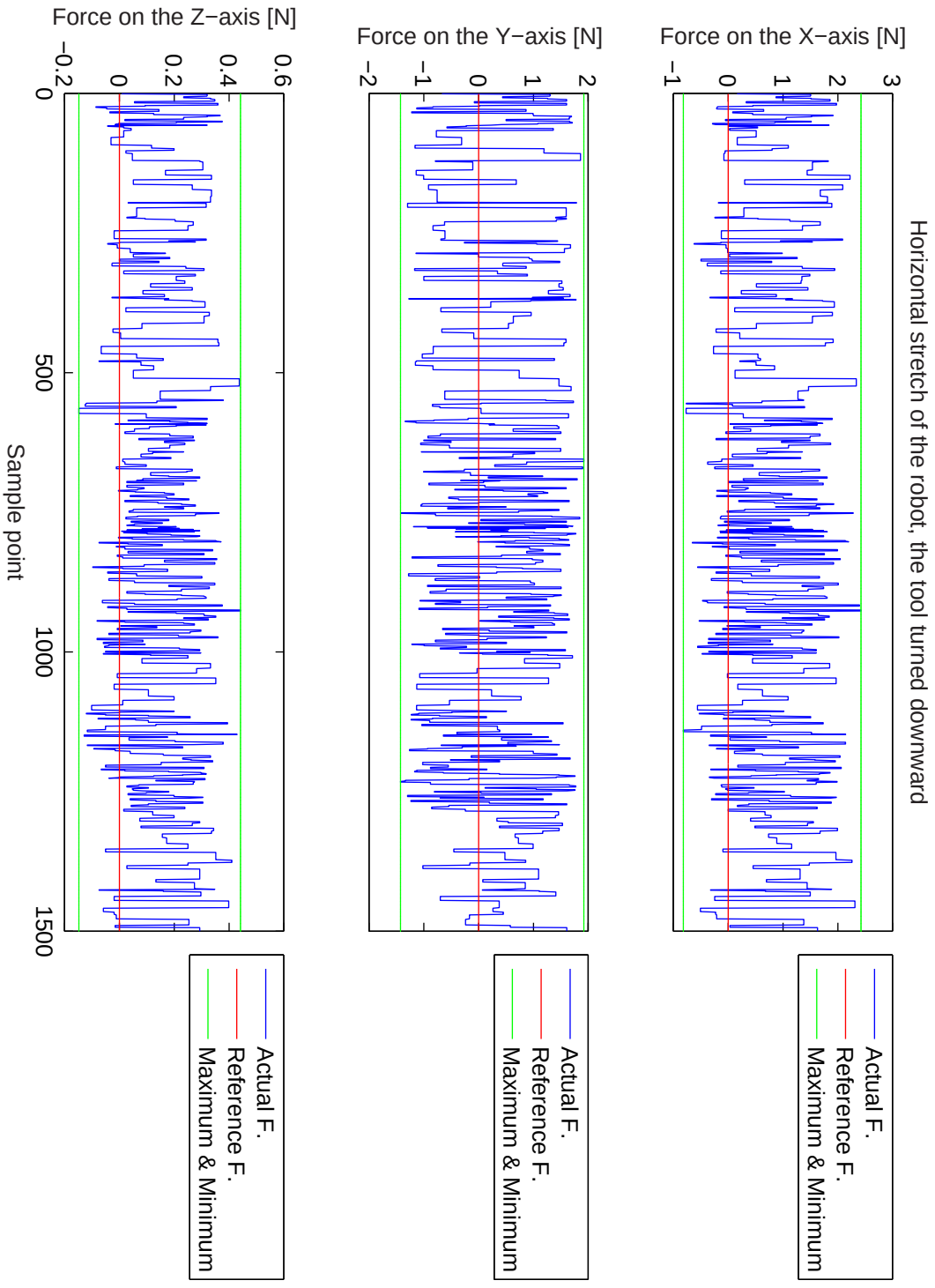

Force on the Z−axis [N]
Force on the Y−axis [N]
Force on the X−axis [N]
Horizontal stretch of the robot, the tool turned downward
Sample point
Actual F.
Reference F.
Maximum & Minimum

Figure A.8: Graphic representation of noise received on the force sensor, when the robot is in a horizontal stretched position with the tool pointing downward

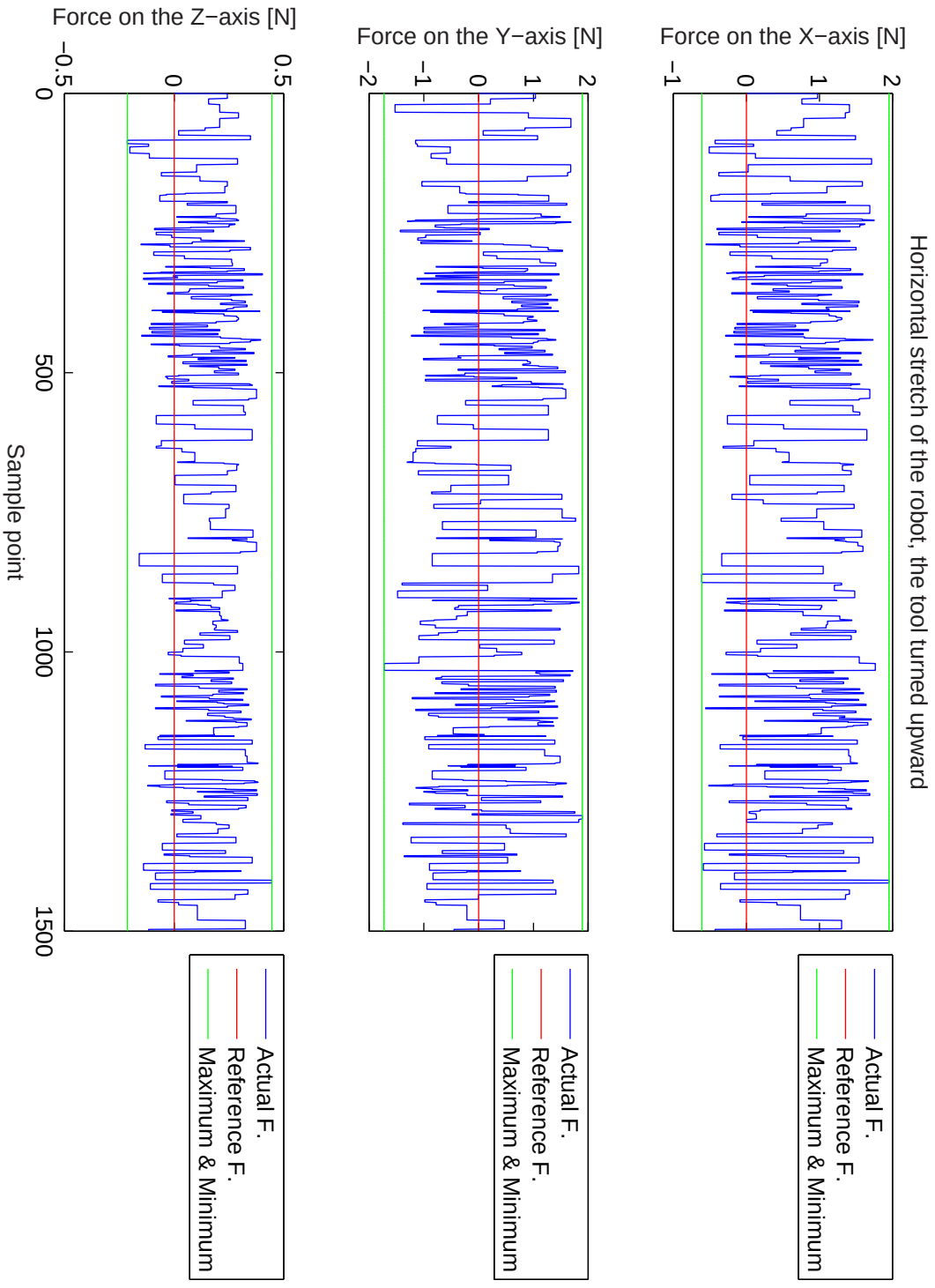

Force on the Z−axis [N]
Force on the Y−axis [N]
Force on the X−axis [N]
Horizontal stretch of the robot, the tool turned upward
Sample point
Actual F.
Reference F.
Maximum & Minimum

Figure A.9: Graphic representation of noise received on the force sensor, when the robot is in a horizontal stretched position with the tool pointing upward

Appendix B

CD List of Contents

9230-05-1278.pdf Drawning of the Mini40-R force sensor

BondyS051976-WahlgreenS042157.pdf Copy of the report with signatures

connectionregulatortest.py Program for all communication between the user-pc and the robot controller

Drawing - deburr.igr Drawing of the model of the deburr tool, opens in SmartSketch

Drawing - deburr.pdf Drawing of the model of the deburr tool

Drawing - tool.igr Drawing of the victim element, opens in SmartSketch

Drawing - tool.pdf Drawing of the victim element, opens in SmartSketch

force.py Program for all communication between the user-pc and the sensor-pc

force_test.py Test program, which reads out data from the sensor for analyze

force_test.txt Test data from force sensor, random position

force_test_deburr1.txt Test data from force sensor, $1^{(}st)$ side position

force_test_deburr2.txt Test data from force sensor, $2^{(}nd)$ side position

force_test_deburr3.txt Test data from force sensor, $3^{(}rd)$ side position

force_test_deburr4.txt Test data from force sensor, $4^{(}th)$ side position

force_test_init.txt Test data from force sensor, init position

force_test_stretch.txt Test data from force sensor, horizontal stretch of robot with tool at maximum range

force_test_stretch_down.txt Test data from force sensor, horizontal stretch of robot with tool downward

force_test_stretch_up.txt Test data from force sensor, horizontal stretch of robot with tool upward

maindeburr.py Main program file

scriptmanual_en.pdf URScript Manual from UR

testit_fourthrun.txt Test data from force sensor, while deburring one element

UR-6-85-5-A_Produktblad_web_UK.pdf Datasheet for the UR–6–85–5–A

Appendix C

Drawing of force sensor

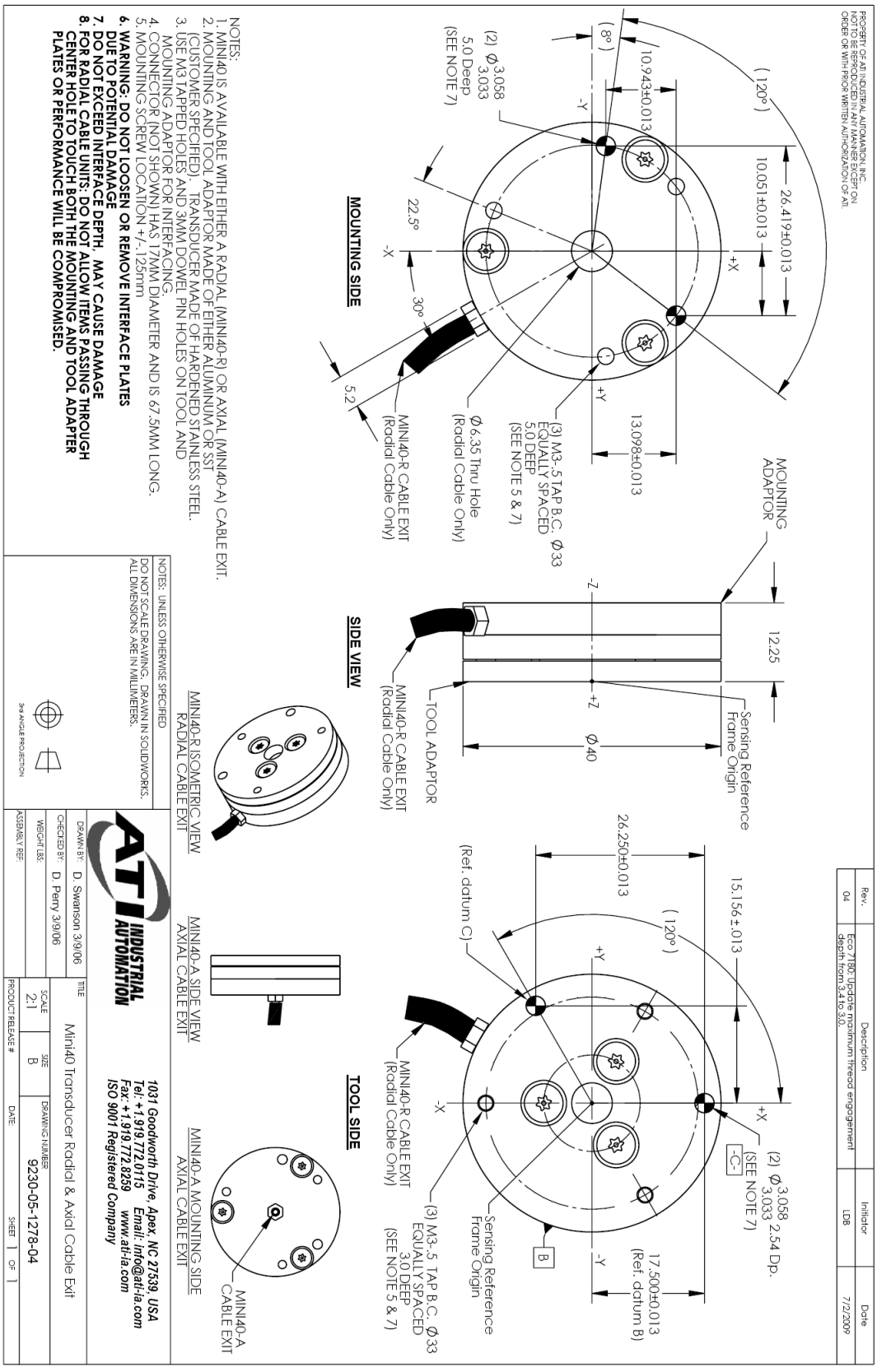

PROPERTY OF ATI INDUSTRIAL AUTOMATION, INC.
NOT TO BE REPRODUCED IN ANY MANNER EXCEPT ON
ORDER OR WITH PRIOR WRITTEN AUTHORIZATION OF ATI.
Rev. 04
Description
Eco 71807: Update maximum thread engagement depth from 3.4 to 3.0.
Initiator LDB
Date 7/2/2009
MOUNTING SIDE
SIDE VIEW
TOOL SIDE
MOUNTING ADAPTOR
TOOL ADAPTOR
Sensing Reference Frame Origin
MINI40-R CABLE EXIT (Radial Cable Only)
(3) M3-.5 TAP B.C. Ø33 EQUALLY SPACED 5.0 DEEP (SEE NOTE 5 & 7)
Ø 6.35 Thru Hole (Radial Cable Only)
(2) Ø 3.058 3.033 5.0 Deep (SEE NOTE 7)
(2) Ø 3.058 3.033 2.54 Dp. (SEE NOTE 7)
(3) M3-.5 TAP B.C. Ø33 EQUALLY SPACED 3.0 DEEP (SEE NOTE 5 & 7)
MINI40-A CABLE EXIT
MINI40-R ISOMETRIC VIEW RADIAL CABLE EXIT
MINI40-A SIDE VIEW AXIAL CABLE EXIT
MINI40-A MOUNTING SIDE AXIAL CABLE EXIT
NOTES:
1. MINI40 IS AVAILABLE WITH EITHER A RADIAL (MINI40-R) OR AXIAL (MINI40-A) CABLE EXIT.
2. MOUNTING AND TOOL ADAPTOR MADE OF EITHER ALUMINUM OR SST (CUSTOMER SPECIFIED). TRANSDUCER MADE OF HARDENED STAINLESS STEEL.
3. USE M3 TAPPED HOLES AND 3MM DOWEL PIN HOLES ON TOOL AND MOUNTING ADAPTOR FOR INTERFACING.
4. CONNECTOR (NOT SHOWN) HAS 17MM DIAMETER AND IS 67.5MM LONG.
5. MOUNTING SCREW LOCATION +/-.125mm
6. WARNING: DO NOT LOOSEN OR REMOVE INTERFACE PLATES DUE TO POTENTIAL DAMAGE
7. DO NOT EXCEED INTERFACE DEPTH. MAY CAUSE DAMAGE
8. FOR RADIAL CABLE UNITS: DO NOT ALLOW ITEMS PASSING THROUGH CENTER HOLE TO TOUCH BOTH THE MOUNTING AND TOOL ADAPTER PLATES OR PERFORMANCE WILL BE COMPROMISED.
NOTES: UNLESS OTHERWISE SPECIFIED
DO NOT SCALE DRAWING. DRAWN IN SOLIDWORKS.
ALL DIMENSIONS ARE IN MILLIMETERS.
INDUSTRIAL AUTOMATION
1031 Goodworth Drive, Apex, NC 27539, USA
Tel: +1.919.772.0115 Email: info@ati-ia.com
Fax: +1.919.772.8259 www.ati-ia.com
ISO 9001 Registered Company
DRAWN BY: D. Swanson 3/9/06
CHECKED BY: D. Perry 3/9/06
WEIGHT LBS:
ASSEMBLY REF:
TITLE
Mini40 Transducer Radial & Axial Cable Exit
SCALE 2:1
SIZE B
DRAWING NUMBER
9230-05-1278-04
PRODUCT RELEASE #
DATE:
SHEET 1 OF 1
3rd ANGLE PROJECTION

Figure C.1: Technical drawing of the force sensor [A.]

Appendix D

Drawing of the victim element

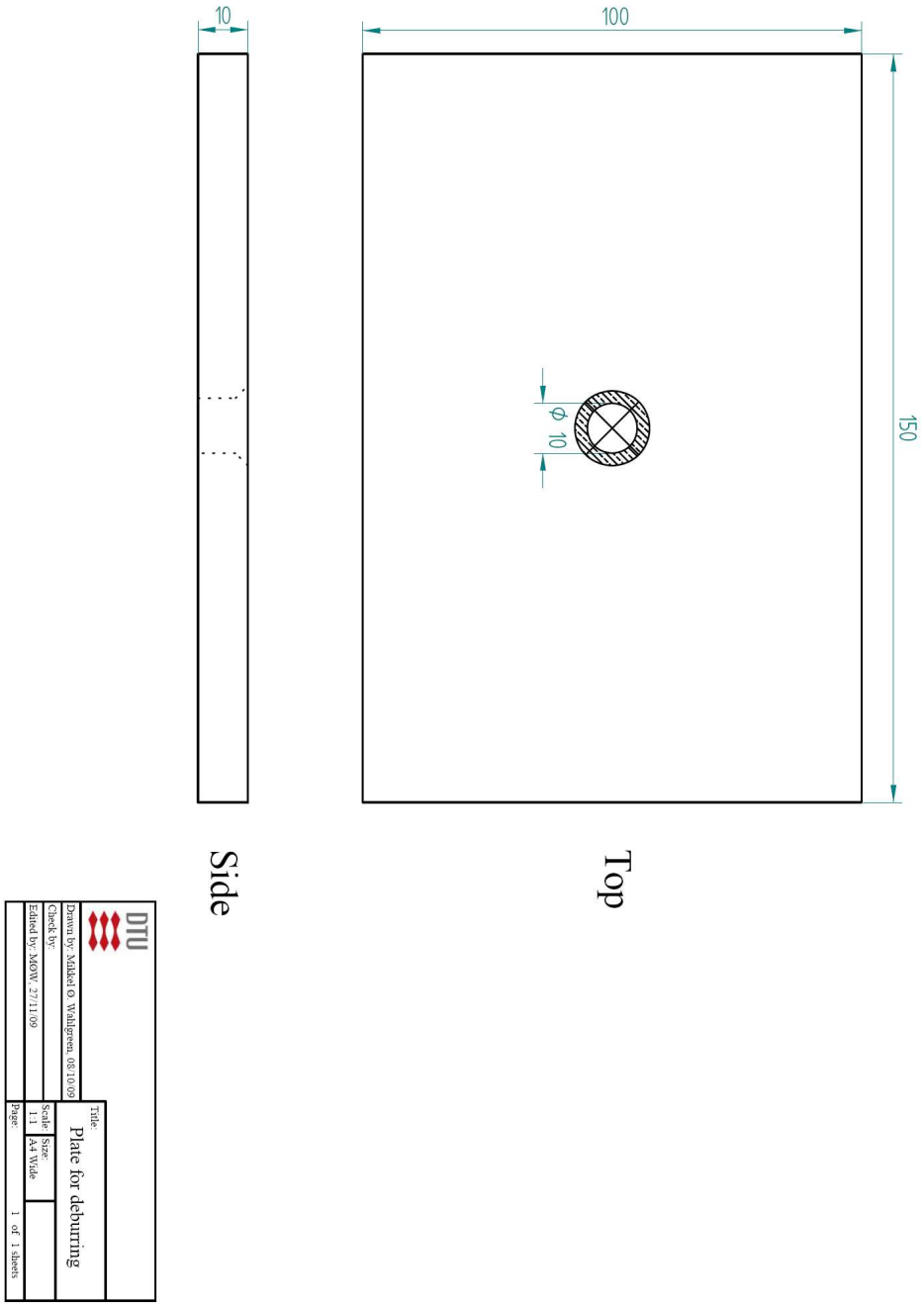


Figure D.1: Technical drawing the victim element, Not in scale, see B

Appendix E

Drawing of the deburr tool model

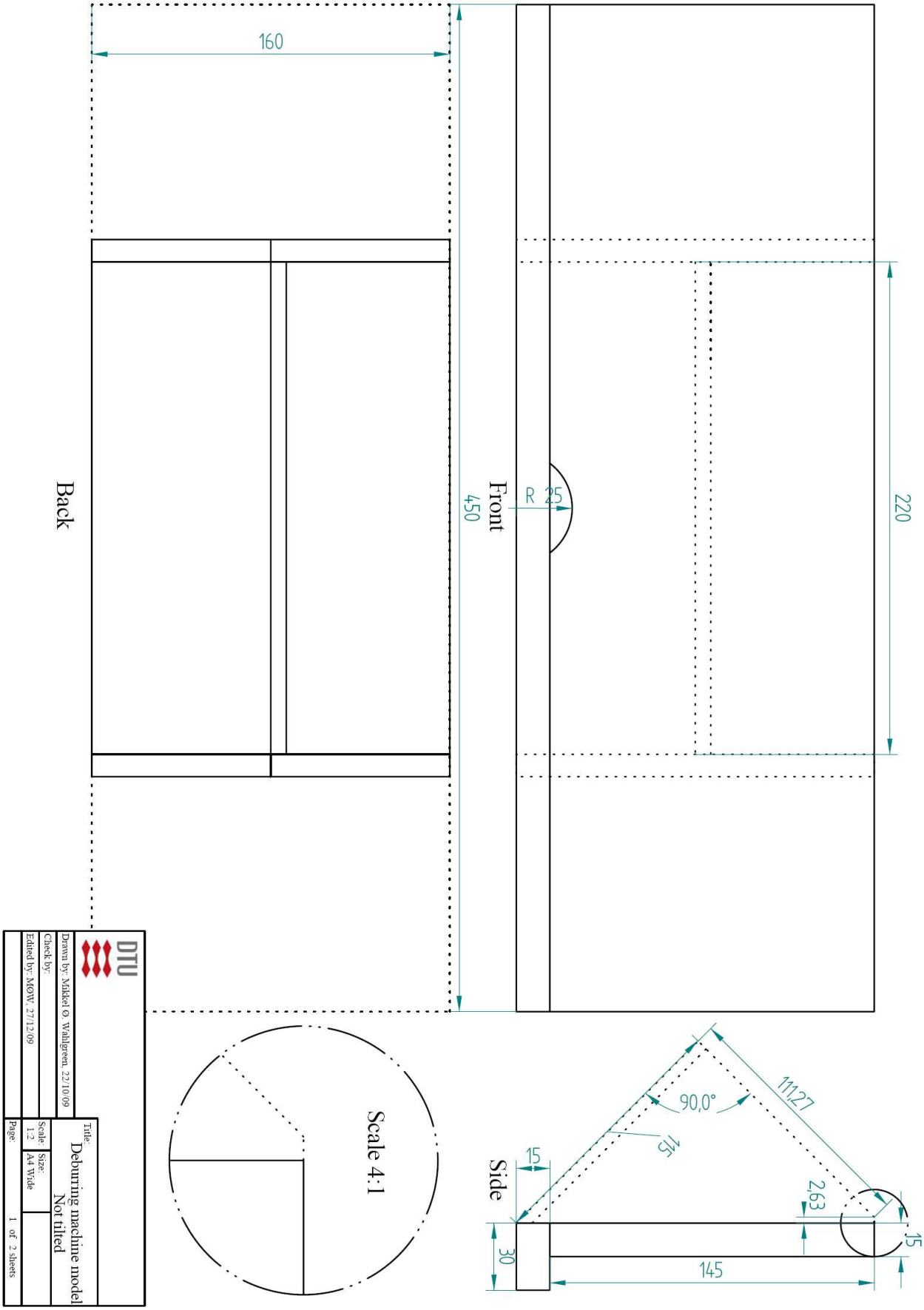


Figure E.1: Technical drawing no. 1 of the deburr tool model, Not in scale, see B

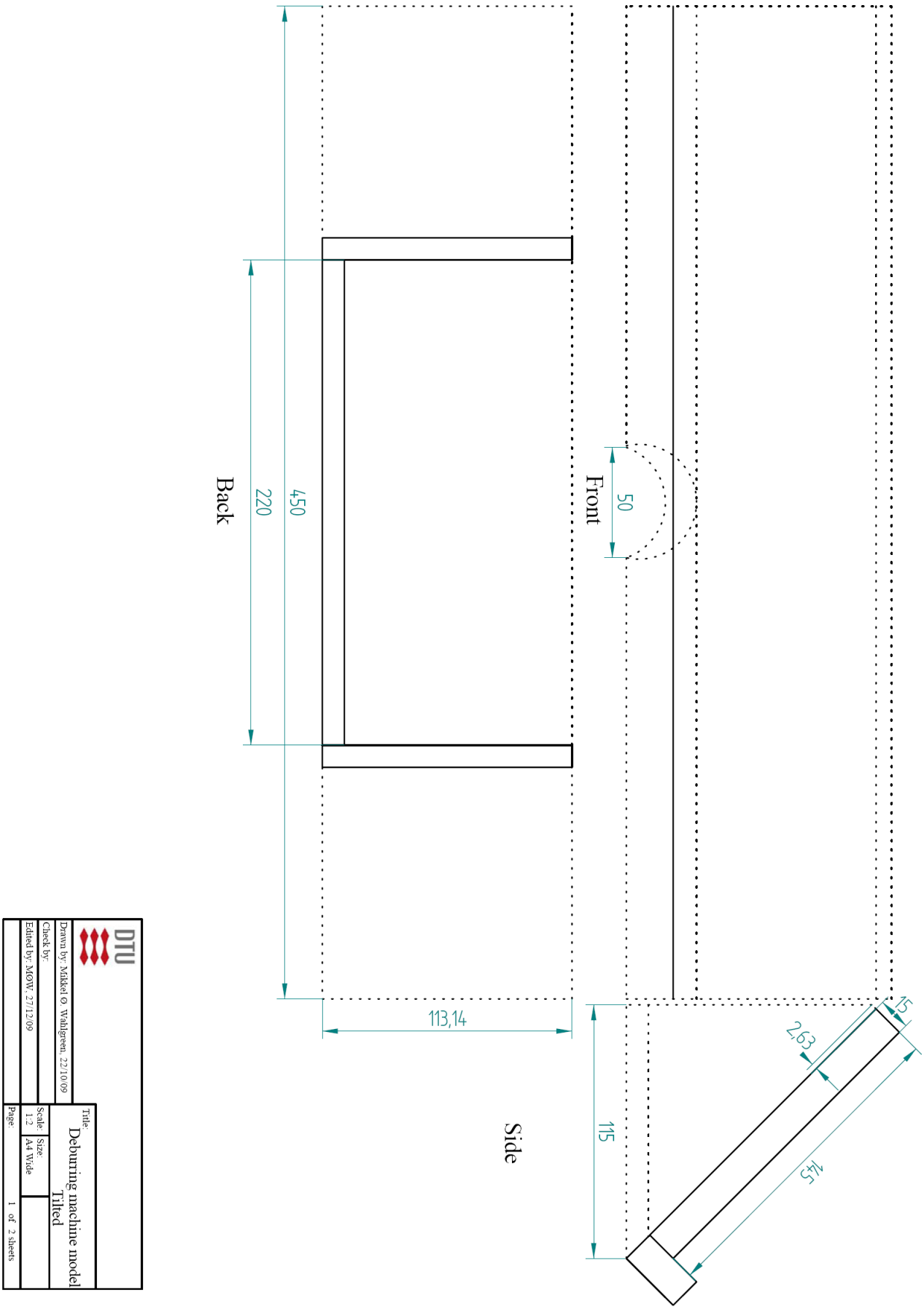


Figure E.2: Technical drawing no. 2 of the deburr tool model, Not in scale, see B

Appendix F

Source code

F.0.1 maindeburr.py

```
# -*- coding: cp1252 -*-

def systemclear(): #This clears the screen depending on the OS used
  import os
  if os.name == "posix":
  # Unix/Linux/MacOS/BSD/etc
    os.system('clear')
  elif os.name in ("nt", "dos", "ce"):
    # DOS/Windows
    os.system('CLS')

import numpy
from numpy import *
import time
import locale
locale.setlocale(locale.LC_NUMERIC, '')
from connectionregulatortest import Connection
from force import Force
c = Connection('192.38.66.237', 30003)
t = 0
while(t==0):
  systemclear()
  print "Moving robot into start position, please wait"
  c.initialize()
  systemclear()
  f =  Force('192.38.66.252', 12345)
  f.bias()
  c.init_variables(4,0.02,0.0005,1)
```

```
plates = 1
print ""
print "########################################"
print "###          Welcome to              ###"
print "###      the deburr program          ###"
print "########################################"
print ""
print "The commands for this program are:"
print "  deburr  =    Start deburring"
print "  debug   =    Enter debug menu"
print "  exit    =    Exit the program"
print ""
print "If no or a wrong input is given"
print "you will return to this screen"
print ""
choice = raw_input("Command: ")
print ""

if choice == "deburr":
  plates = raw_input("How many plates should be deburred? (MAX 10): ")
  try:
    plates = float(plates)
  except Exception,e:
    print "Error! ", e," Please make sure you put in a number between 1-
    exit("\nTry starting the program again\n")
  if plates > 10:
    print ""
    print "########################################"
    print "###    Deburring plates 10    ###"
    print "########################################"
    print ""
    plates = 10
  elif plates <= 0:
    print ""
    print "########################################"
    print "### NOT Deburring any plates  ###"
    print "########################################"
    print ""
    time.sleep(3)
  deburred_plates = 0
  systemclear()
  while deburred_plates < plates:
    print ""
```

```
      print "#########################################"
      print "###    Plate no %s is running    ###" % str(deburred_plates+1)
      print "#########################################"
      print ""
      global turncounter
      turncounter = 0
      c.collect(turncounter)
      c.deburr(turncounter)
      c.deliver()
      deburred_plates = deburred_plates + 1
    c.initialize()
    systemclear()
    print ""
    print "#########################################"
    print "### Finished deburring plates  ###"
    print "#########################################"
    print ""

  if choice == "debug":
    t = 1


  if choice == "exit":
                systemclear()
                try:
                    myfile
                except NameError:
                    myfile = None

                try:
                    myfile2
                except NameError:
                    myfile2 = None

                try:
                    myfile3
                except NameError:
                    myfile3 = None

                if myfile is None:
                    myfile = 1
                else:
                   #print "Test: %s" % myfile.closed
```

```
                    myfile.close()
                    #print "Myfile is closed"

                if myfile2 is None:
                    myfile = 1
                else:
                    #print "Test: %s" % myfile.closed
                    myfile2.close()
                    #print "Myfile2 is closed"

                if myfile3 is None:
                    myfile = 1
                else:
                    #print "Test: %s" % myfile.closed
                    myfile3.close()
                    #print "Myfile3 is closed"

                c.connect()
                c.close()
                exit("\nBuy\n")

    choice = ""


#Debugmode, the old interface adopted partly from Orn & Einir
while(1):
    print "pos       -   display current robot position"
    print "init      -   initialize the robot"
    print "force     -   current force reading"
    print "bias      -   remove force bias"
    print "goto      -   goto cartesian position"
    print "move      -   translate end effector"
    print "test      -   Rotation test movement from python"
    print "random    -   testing of controller speed, not working properly"
    print "exit      -   exits program"
    print "approachx-   for testing purpose only"
    print "approachy-   for testing purpose only"
    print "col       -   Collect plate"
    print "del       -   Deliver plate"
    print "deburr    -   Deburr program"
    selection = raw_input("Enter your selection: ")
```

```
if selection == "init":
  systemclear()
  global cost
  print ""
  print "##########"
  print "initializing robot"
  print "##########"
  print ""
  import time
  c.initialize()
  f =  Force('192.38.66.252', 12345)
  f.bias()
  c.init_variables(2,0.03,0.0015,1)
  print "Please wait until the robot has stopped moving, before calling a
  print ""


if selection == "bias":
  systemclear()
  print ""
  print "##########"
  print "initializing Force Sensor"
  print "##########"
  print ""
  f =  Force('192.38.66.252', 12345)
  f.bias()


if selection == "goto":
  systemclear()
  c.establish_connection()
  results = c.read_socket_stream()
  f = c.forward_kin(results.values[30],results.values[31],results.values[
  print ""
  print "##########"
  print "Current robot position is: [%.6f,%.6f,%.6f]" %(f[0],f[1],f[2])
  print "##########"
  print ""
  x = raw_input("Enter X coordinate [m]: ")
  y = raw_input("Enter Y coordinate [m]: ")
  z = raw_input("Enter Z coordinate [m]: ")
  c.send_cartesian_to_socket(float(x),float(y),float(z))
  systemclear()
```

```
if selection == "move":
  systemclear()
  c.establish_connection()
  results = c.read_socket_stream()
  f = c.forward_kin(results.values[30],results.values[31],results.values[
  c.close()
  x = raw_input("Enter X displacement [m]: ")
  y = raw_input("Enter Y displacement [m]: ")
  z = raw_input("Enter Z displacement [m]: ")
  c.init_variables(2,0.03,0.0015,1)
  c.translate(float(x),float(y),float(z),0,0,0)
  c.establish_connection()
  results = c.read_socket_stream()
  f2 = c.forward_kin(results.values[30],results.values[31],results.values[
  c.close()
  print "Total movement was: [%.4f,%.4f,%.4f]" %(f2[0]-f[0],f2[1]-f[1],f2[


if selection == "pos":
  systemclear()
  c.establish_connection()
  results = c.read_socket_stream()
  f = c.forward_kin(results.values[30],results.values[31],results.values[
  c.close()
  myfile = open("data.txt", "a")
  myfile.write("%.17f,%.17f,%.17f,%.17f,%.17f,%.17f\n" %(results.values[3
  myfile.close()
  print ""
  print "##########"
  print "Current robot position is: [%.6f,%.6f,%.6f]" %(f[0],f[1],f[2])
  print "##########"
  print ""


if selection == "force":
  systemclear()
  f =  Force('192.38.66.252', 12345)
  f.establish_connection()
  f.send_to_socket()
  force = f.read_socket_stream()
  c.establish_connection()
```

```
    results = c.read_socket_stream()
    f2 = c.force_rotation(results.values[30],results.values[31],results.val
    print ""
    print "##########"
    print "Current force vector in force sensor coordinate system is: [%.4s
    print "With respect to robot coordinate system: [%.4sN,%.4sN,%.4sN]" %
    print "##########"
    print ""

#Not in use
  if selection == "test":
    systemclear()
    global cost
    print ""
    print "##########"
    print "initializing robot, afterwards, you're welcome to give a new po
    print "##########"
    print ""
    import time
    c.initialize()
    time.sleep(3)
    f =  Force('192.38.66.252', 12345)
    f.establish_connection()
    f.send_to_socket()
    force = f.read_socket_stream()
    if force[2] > 0.1:
      f.send_to_socket_init()
    c.init_variables(2,0.03,0.0015,1)
    newx = raw_input("Choose a new x position:")
    newy = raw_input("Choose a new y position:")
    newz = raw_input("Choose a new z position:")
    c.connect()
    #c.socket.send("movel(p[%f, %f, %f, 0.0, 1.57, 0],a=0.01,v=0.01,t=10)\r
    c.socket.send("movel(p[0.475, -0.119, 0.604, %f, %f, %f],a=0.01,v=0.01
    c.socket.close()


  if selection == "random":
   systemclear()
   print ""
   print "##################################################################################
   print "###### Robot is been tested, analyse randomit.txt after each run
######"
```

```
    print "#########################################################################################################
    print ""
    #myfile3 = open("randomit.txt", "w")
    values = c.random()
    #myfile3.write('%d \n' % double(values[0]))
    #myfile3.close()


  if selection == "exit":
    systemclear()
    try:
      myfile
    except NameError:
      myfile = None

    try:
      myfile2
    except NameError:
      myfile2 = None

    try:
      myfile3
    except NameError:
      myfile3 = None

    if myfile is None:
      myfile = 1
    else:
      myfile.close()

    if myfile2 is None:
      myfile = 1
    else:
      myfile2.close()

    if myfile3 is None:
      myfile = 1
    else:
      myfile3.close()

    c.connect()
    c.close()
    exit("\nBuy\n")
```

```
  if selection == "approachx":
    systemclear()
    print "Testing X force"
    c.approach_zx_x(-1)


  if selection == "approachy":
    systemclear()
    print "Testing Y force"
    c.approach_y_z(-1)


  if selection == "approachz":
    systemclear()
    print "Testing Z force"
    c.connect()
    results = c.test_receive(1)
    c.socket.send("movej([%s, %s, %s, -1.7, %s, %s], a=2.0, v=2.0)\n" % (re
    c.close()
    time.sleep(5)
    c.approach_z_z(-1)

#Not in use
  if selection == "turn":
    systemclear()
    c.rotate(3)


  if selection == "col":
    systemclear()
    #Move to collect position
    c.collect()
    time.sleep(0.5)
    #Remove bias/gravity on force sensor
    f =  Force('192.38.66.252', 12345)
    f.bias()
    #Approach to table
    c.approach_z_x(-1)
    #Activate Suctionscop
    systemclear()
    print ""
```

```
    print "#########################"
    print "### Securing plate ###"
    print "#########################"
    print ""
    time.sleep(3)


  if selection == "del":
    while(1):
      systemclear()
      #Move to collect position
      c.deliver()
      time.sleep(0.2)
      #Remove bias/gravity on force sensor
      f =  Force('192.38.66.252', 12345)
      f.bias()
      #Approach to table
      c.approach_z_x(-1)
      #Deactivate Suctionscop
      systemclear()


  if selection == "deburr":
    systemclear()
    print "Moving robot into start position, please wait"
    c.initialize()
    systemclear()
    f =  Force('192.38.66.252', 12345)
    f.bias()
    c.init_variables(4,0.02,0.0005,1)
    plates = 1
    plates = raw_input("How many plates should be deburred? (MAX 10): ")
    try:
      plates = float(plates)
    except Exception,e:
      print "Error! ", e," Please make sure you put in a number between 1-
      exit("\nTry starting the program again\n")
    if plates > 10:
      print ""
      print "########################################"
      print "###     Deburring plates 10     ###"
      print "########################################"
      print ""
```

```
      plates = 10
    elif plates <= 0:
      print ""
      print "#########################################"
      print "### NOT Deburring any plates  ###"
      print "#########################################"
      print ""
      time.sleep(3)
    deburred_plates = 0
    systemclear()
    while deburred_plates < plates:
      print ""
      print "#########################################"
      print "###    Plate no %s is running    ###" % str(deburred_plates+1)
      print "#########################################"
      print ""
      turncounter = 0
      c.collect(turncounter)
      c.deburr(turncounter)
      c.deliver()
      deburred_plates = deburred_plates + 1
    c.initialize()
    systemclear()
    print ""
    print "#########################################"
    print "### Finished deburring plates  ###"
    print "#########################################"
    print ""

#In use?
  if selection == "deburrpos":
    systemclear()
    c.move_to_deburr_pos()
    time.sleep(5)

#In use?
  if selection == "toolend":
    c.connect()
    results = c.test_receive(1)
    print results.values[35]
    time.sleep(5)

  selection = ""
```

F.0.2 connectionregulatortest.py

```
# TCP client
import numpy
from numpy import *
import socket
socket.setdefaulttimeout( 1.0 )
#from time import clock, time
from time import *
#import time
import time
import locale
locale.setlocale(locale.LC_NUMERIC, '')
import struct
from force import Force
import locale
locale.setlocale(locale.LC_NUMERIC, '')

class Connection:
  def __init__(self, ip, port): #Init of the Connection program, By Orn &
    self.ip = ip
    self.port = port

  def connect(self): #Connector, Partly by Orn & Einir
    self.socket = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
    try:
      data2 = self.socket.connect((self.ip, self.port))
    except Exception,e:
      print "Error! Socket error was: ", e, " Remember to establish connect
      exit("\nBuy\n")
    self.socket.settimeout(1.0)

  def establish_connection(self): #Establish the connection, By Orn & Einir
    self.connect()

  def test_receive(self, n): #Function that reads the socket stream and ret
    for i in range(n):
      try:
        data = self.read_socket_stream()
      except Exception,e:
        print i, "Error! ", e, " trying to reconnect"
        self.establish_connection()
      return data
```

```
  def test_receive2(self, n, force): #Function that takes force vector as i
    for i in range(n):
      try:
        data = self.read_socket_stream()
        p = self.forward_kin(data.values[30],data.values[31],data.values[32
        f = self.force_rotation(data.values[30],data.values[31],data.values
      except Exception,e:
        print i, "Error! ", e, " trying to reconnect"
        self.establish_connection()
      #f = [0 0 0]
    return array([[p,f]])

  def read_socket_stream(self): #Function that converts the bytestream, fro
    msg_size, time = struct.unpack('>id', self.socket.recv(12)) #4(int) + 8
    msg_size = msg_size - 12
    data = self.socket.recv(msg_size)
    values = struct.unpack('>%dd'%(msg_size/8), data)
    return Results(time, values)

  def initialize(self): #Moves the robot to start position, Partly by Orn &
    self.connect()
#   pos = [0.000000, -1.553417118727561, -1.5863126739797573, -0.036943518
    pos = [0.000000, -1.553417118727561, -1.5863126739797573, -0.036943518
    pos1 = [0.00, -1.55, -1.58, -0.03, 1.57, 0.01]
    self.socket.send("movej(%s, a=1.0, v=0.31975511965976)\n" % pos)
#   self.socket.send("movej([-0.001279959781185732, -1.553417118727561, -1
    i=0
    while (i < 5): #While loop, which controls that the robot have moved in
       results = self.read_socket_stream()
       if results.values[i+30] <= pos[i]+0.001 and results.values[i+30] >=
         i = i + 1
       #print "%s" % (i)
    self.socket.close()

  def init_variables(self,Fref,speed,kp,lagbust): #Sets all global constant
    global approach_speed
    global GFref
    global Kpf
    global cost
    global cost_counter
    global lagbuster
    global Kpf_matrix
```

```
    approach_speed = float(speed)
    GFref = float(Fref)
    Kpf = float(kp)
    cost = zeros((1,15))
    cost_counter = 0
    Kpf_matrix = zeros((1,15))
    Kpf_counter = 0
    Way = 0
    lagbuster = int(lagbust)
    self.connect()
    self.socket.send("set_payload(0.5)")
    self.socket.close()

  def force_rotation(self,t1,t2,t3,t4,t5,t6,Fo): #Convert force data from f
    a2 = -0.425
    a3 = -0.39243
    d1 = 0.0892
    d4 = 0.109
    d5 = 0.093
    d6 = 0.082
    T01 = array([[cos(t1),0,sin(t1),0],[sin(t1),0,-cos(t1),0],[0,1,0,d1],[0
    T12 = array([[cos(t2),-sin(t2),0,a2*cos(t2)],[sin(t2),cos(t2),0,a2*sin(
    T23 = array([[cos(t3),-sin(t3),0,a3*cos(t3)],[sin(t3),cos(t3),0,a3*sin(
    T34 = array([[cos(t4),0,sin(t4),0],[sin(t4),0,-cos(t4),0],[0,1,0,d4],[0
    T45 = array([[cos(t5),0,-sin(t5),0],[sin(t5),0,cos(t5),0],[0,-1,0,d5],[
    T56 = array([[cos(t6),-sin(t6),0,0],[sin(t6),cos(t6),0,0],[0,0,1,d6],[0
    T06 = dot(T01,dot(T12,dot(T23,dot(T34,dot(T45,T56)))))

    R = zeros((3,3))
    R[0,0] = T06[0,0]
    R[0,1] = T06[0,1]
    R[0,2] = T06[0,2]
    R[1,0] = T06[1,0]
    R[1,1] = T06[1,1]
    R[1,2] = T06[1,2]
    R[2,0] = T06[2,0]
    R[2,1] = T06[2,1]
    R[2,2] = T06[2,2]

    F = zeros((3,1))
    F[0,0] = Fo[0]
    F[1,0] = Fo[1]
    F[2,0] = Fo[2]
```

```
    K = dot(R,F)
    K[2,0] = K[2,0]*(-1) # because of 180 degree difference between Z axes
    return K

  def send_speed_to_socket(self,Xspeed,Yspeed,Zspeed,time): #Sends speedl c
    self.socket.send("speedl([%f, %f, %f, 0.0, 0.0, 0.0],1,%f)\n" % (Xspeed


  def send_cartesian_to_socket(self,Xpos,Ypos,Zpos): #Sends coodinates to t
    self.connect()
    self.socket.send("movel(p[%f, %f, %f, 0.0, 1.57, 0],a=0.01,v=0.01,t=10)
    self.socket.close()

  def polynomial(self,begin,end,tf): #Cubic polynomial, By Orn & Einir
    if tf < 0.1:
      tf = 0.1
    res = 125./3. #Resolution: the rate that we send commands to the robot
    t = arange(0,tf,1/(float(res))) #Make a time vector
    a0 = begin
    a2 = 3./tf**2*(end-begin)
    a3 = -2./tf**3*(end-begin)
    position = zeros((1,len(t)))
    speed = zeros((1,len(t)))
    for i in range(len(t)):
      position[(0,i)] = a0 + a2*t[i]**2 + a3*t[i]**3
      speed[(0,i)] = 2 * a2 * t[i] + 3 * a3 * t[i]**2
    return [position,speed]

  def polynomial2(self,begin,end,tf,resolution): #Cubic polynomial, takes r
    if tf < 0.1:
      tf = 0.1
    res = float(resolution) #Resolution: the rate that we send commands to
    t = arange(0,tf,1/(float(res))) #Make a time vector
    a0 = begin
    a2 = 3./tf**2*(end-begin)
    a3 = -2./tf**3*(end-begin)
    position = zeros((1,len(t)))
    speed = zeros((1,len(t)))
    for i in range(len(t)):
      position[(0,i)] = a0 + a2*t[i]**2 + a3*t[i]**3
      speed[(0,i)] = 2 * a2 * t[i] + 3 * a3 * t[i]**2
    return [position,speed]
```

```
  def calculate_time(self,beginX,beginY,beginZ,endX,endY,endZ): #Function t
    tf = (sqrt((beginX-endX)**2+(beginY-endY)**2+(beginZ-endZ)**2))/0.05
    return tf

  def translate(self,Xend,Yend,Zend,Fref,turncounter,Freg,res): #Function t
    self.connect()
    results = self.test_receive(1)
    f = self.forward_kin(results.values[30],results.values[31],results.valu
    regulatorbreytaX = f[0]
    regulatorbreytaY = f[1]
    regulatorbreytaZ = f[2]
    self.close()

    T = self.calculate_time(0,0,0,Xend,Yend,Zend)

    k1 = self.polynomial2(0,Xend,T,res)
    k2 = self.polynomial2(0,Yend,T,res)
    k3 = self.polynomial2(0,Zend,T,res)
    K = [k1[0]+regulatorbreytaX,k2[0]+regulatorbreytaY,k3[0]+regulatorbreyt
    self.draw(K,Fref,turncounter,Freg)

  def draw(self,k,Fref,turncounter,Freg): #Important function: Works as po
    #The function also writes position and force data to a file for further
    Xp=k[0] #X position
    Yp=k[1] #Y position
    Zp=k[2] #Z position
    Xd=k[3] #X speed
    Yd=k[4] #Y speed
    Zd=k[5] #Z speed
    #myfile = open("draw.txt", "a")

    #Initialize variables
    correctionX = 0
    correctionY = 0
    correctionZ = 0
    integratorX = 0
    integratorY = 0
    integratorZ = 0
    correction = 0
    integratorFx = 0 #added for regulation on plates
    integratorFy = 0 #added for regulation on plates
    integratorFz = 0 #Orns original regulation
```

```
    global GFref
    Fref = GFref
    global lagbuster #If lagbuster is on, then the program will clear the s

    ######################################################################
    ############ Regulation in sensor Z-axis ###############
    ######################################################################

    counter = 1
    i=0
    self.connect()
    myfile = open("testit.txt", "a")
    fo =  Force('192.38.66.252', 12345)
    fo.establish_connection()
    global Kpf
    for j in range(Xd.shape[1]*3):
      results = self.test_receive(1)
      if counter == 3: #Sending commands at 41.6Hz, 125Hz/3
        time1 = clock()
#       print "####moving####"

        self.send_speed_to_socket(Xd[(0,i)]+correctionX,Yd[(0,i)]+correctio
        fo.send_to_socket()
        force = fo.read_socket_stream()
        myfile4 = open("draw.txt", "a")
        myfile4.write('%f %f %f %f %f %f %f\n' % (Xd[(0,i)],correctionX,Yd[
        myfile4.close()
        f = self.forward_kin(results.values[30],results.values[31],results.

        ###Error and Integration###
        errorX = Xp[(0,i)]-f[0]
        errorY = Yp[(0,i)]-f[1]
        errorZ = Zp[(0,i)]-f[2]
        integratorX = integratorX + errorX
        integratorY = integratorY + errorY
        integratorZ = integratorZ + errorZ

        errorFz = Fref - force[2]

        ##########Corrections###########
        ###Force PI Regulator###
        integratorFz = integratorFz + errorFz
        Kif = 0.0005/20
```

```
        correctionX = Kpf*errorFz + Kif*integratorFz

        ###Position PI Regulator###
        Kp = 5
        Ki = 0.05
        correctionY = Kp*errorY + Ki*integratorY
        correctionZ = Kp*errorZ + Ki*integratorZ

        if Freg == 0:
          correctionX = 0
          correctionY = 0
          correctionZ = 0

        #Write position, speed, control signal and force data to a file
        myfile.write('%f %f %f %f %f %f %f %f %f %f\n' % (Xd[(0,i)],Yd[(0,i

        counter = 0;
        i=i+1;
        time2 = clock()
        #This routine clears the socket buffer if lag is detected
        if lagbuster == 1:
          if time2-time1 > 0.1:
            print "#########Lag detected######### Clearing %i socket packets"
            for count in range(1, 5+int(floor(125*(time2-time1)))):
              self.test_receive(1)
      counter = counter + 1;
    self.close()

  def forward_kin(self,t1,t2,t3,t4,t5,t6): #Calculate forward kinematics by
    a2 = -0.425
    a3 = -0.39243
    d1 = 0.0892
    d4 = 0.109
    d5 = 0.093
    d6 = 0.082
    T01 = array([[cos(t1),0,sin(t1),0],[sin(t1),0,-cos(t1),0],[0,1,0,d1],[0
    T12 = array([[cos(t2),-sin(t2),0,a2*cos(t2)],[sin(t2),cos(t2),0,a2*sin(
    T23 = array([[cos(t3),-sin(t3),0,a3*cos(t3)],[sin(t3),cos(t3),0,a3*sin(
    T34 = array([[cos(t4),0,sin(t4),0],[sin(t4),0,-cos(t4),0],[0,1,0,d4],[0
    T45 = array([[cos(t5),0,-sin(t5),0],[sin(t5),0,cos(t5),0],[0,-1,0,d5],[
    T56 = array([[cos(t6),-sin(t6),0,0],[sin(t6),cos(t6),0,0],[0,0,1,d6],[0
    T06 = dot(T01,dot(T12,dot(T23,dot(T34,dot(T45,T56)))))
    x = T06[0,3]+0.0606
```

```
    y = T06[1,3]
    z = T06[2,3]
    return [x,y,z]

  def approach(self): #Moves the robot near the blackboard, By Orn & Einir
    self.connect()
    fo =  Force('192.38.66.252', 12345)
    fo.establish_connection()
    counter = 0
    while(1):
      counter = counter + 1
      results = self.test_receive(1)
      if counter == 3: #Sending commands at 41Hz, 125Hz/3
        fo.send_to_socket()
        force = fo.read_socket_stream()
        if force[2] < 0.4:
          self.send_speed_to_socket(approach_speed,0.0,0.0,0.04)
        else:
          self.send_speed_to_socket(0.0,0.0,0.0,0.04)
          self.close()
          break
        counter = 0

  def write_to_file(self,matrix): #Writes out data into a file, By Orn & E
    myfile = open("output.txt", "w")
    for i in range(matrix.shape[1]):
      myfile.write('%f\n' % (matrix[(0,i)]))

  def position(self): #Reads out the position of the robot, By Orn & Einir
    self.establish_connection()
    results = self.read_socket_stream()
    pos = self.forward_kin(results.values[30],results.values[31],results.va
    self.close()
    return pos

  def __del__(self): #Fundamental function in Python, Called when the insta
    self.close()

  def close(self): #Close down every socket connection
    if self.socket:
      self.socket.close()

  def random(self): #Function to test send and receive speed from robot
```

```
    t = 0
    myfile3 = open("randomit.txt", "a")
    while t<5:
      self.connect()
      s2 = self.socket.send("random()")
      s = self.read_random()
      myfile3.write('S2: %s S: %s t: %f\n' % (s2,s,t))
      t = t + 1
      self.socket.close()
    myfile3.close()
    return s

  def read_random(self): #Function to read out the returned msg from robot
    msg_size, time = struct.unpack('>id', self.socket.recv(12)) #4(int) + 8
    msg_size = msg_size - 12
    data = self.socket.recv(msg_size)
    values = struct.unpack('>%dd' % (msg_size/8), data)
    values2 = array([[str(values[55])],[str(values[56])]])
    myfile = open("data.txt", "a")
    t = 0
    while t < 11:
      myfile.write('value 40 indeholder %s\n' % (values[40]))
      myfile.write('value 55 indeholder %s\n' % (values[55]))
      myfile.write('value 56 indeholder %s\n' % (values[56]))
      myfile.write('value 60 indeholder %s\n' % (values[60]))
      t = t+1
    myfile.close()
    return [values2[0],values2[1]]

  def approach_z_x(self,direction): #When the x direction of the sensor are
    self.connect()
    fo =  Force('192.38.66.252', 12345)
    fo.establish_connection()
    counter = 0
    i = 0
    while(1):
       i = i+1
       counter = counter + 1
       results = self.test_receive(1)
       if counter == 10: #Sending commands at 41Hz, 125Hz/3
         fo.send_to_socket()
         force = fo.read_socket_stream()
         if force[2] > -3.0 and force[2] < 3.0:
```

```
            if direction == -1:
              self.send_speed_to_socket(0.0,0.0,-approach_speed,0.04) #Moves
            elif direction == 1:
              self.send_speed_to_socket(0.0,0.0,approach_speed,0.04) #Moves
          elif force[2] > 3.0:
            self.send_speed_to_socket(0.0,0.0,0.0,0.04)
            self.close()
            break
          elif force[2] < -3.0:
            self.send_speed_to_socket(0.0,0.0,0.0,0.04)
            self.close()
            break
          else:
            self.send_speed_to_socket(0.0,0.0,0.0,0.04)
            self.close()
            break
          counter = 0

  def approach_zx_x(self,zdirection,xdirection, f,ref): #When the x directi
    self.connect()
    fo =  Force('192.38.66.252', 12345)
    fo.establish_connection()
    counter = 0
    i = 0
    while(1):
      i = i+1
      counter = counter + 1
      results = self.test_receive(1)
      if counter == 10: #Sending commands at 41Hz, 125Hz/3
        fo.send_to_socket()
        force = fo.read_socket_stream()
        if force[f] > -ref and force[f] < ref:
          if zdirection == -1:
            if xdirection == -1:
              self.send_speed_to_socket(-approach_speed/4,0.0,-approach_spe
            elif xdirection == 1:
              self.send_speed_to_socket(approach_speed/4,0.0,-approach_spee
          elif zdirection == 1:
            if xdirection == -1:
              self.send_speed_to_socket(-approach_speed/4,0.0,approach_spee
            elif xdirection == 1:
              self.send_speed_to_socket(approach_speed/4,0.0,approach_speed
        elif force[f] > ref:
```

```
            self.send_speed_to_socket(0.0,0.0,0.0,0.04)
            self.close()
            break
          elif force[f] < -ref:
            self.send_speed_to_socket(0.0,0.0,0.0,0.04)
            self.close()
            break
          else:
            self.send_speed_to_socket(0.0,0.0,0.0,0.04)
            self.close()
            break
          counter = 0

    def decouple(self, plane, distance,turncounter): #Function which moves th
      if plane == "x" or plane == "X":
        self.translate(distance,0.0,0.0,0,turncounter,0,125./3.)
      elif plane == "y" or plane == "Y":
        self.translate(0.0,distance,0.0,0,turncounter,0,125./3.)
      elif plane == "z" or plane == "Z":
        self.translate(0.0,0.0,distance,0,turncounter,0,125./3.)
      else:
        print "Error! The one or both inputs in decouple are wrong"

    def rotate(self, counter): #Function which rotates the TCP of the robot v
     if counter == 0: # Rotate to start position (~-0 degress)
       self.connect()
       results = self.test_receive(1)
       pos = [0.17551645190320445]
       self.socket.send("movej([%s, %s, %s, %s, %s, %s], a=2.0, v=2.0)\n" % (
       i = 0
       while (i <= 0):
         results = self.read_socket_stream()
         if results.values[35] <= pos[0]+0.005 and results.values[35] >= pos[
           f =  Force('192.38.66.252', 12345)
           f.bias()
           break
       self.socket.close()

     elif counter == 1: # Rotate to second position (~-90 degress)
       self.connect()
       results = self.test_receive(1)
       pos = [-1.570796327+0.17551645190320445]
       self.socket.send("movej([%s, %s, %s, %s, %s, %s], a=2.0, v=2.0)\n" % (
```

```
    i = 0
    while (i == 0):
      results = self.read_socket_stream()
      if results.values[35] <= pos[0]+0.005 and results.values[35] >= pos[
        f =  Force('192.38.66.252', 12345)
        f.bias()
        break
    self.socket.close()
    myfile = open("data.txt", "a")
    myfile.write('%s, %s, %s, %s, %s, %s\n' % (results.values[30],results.
    myfile.close()

  elif counter == 2: # Rotate to third position (~-135 degress)
    self.connect()
    results = self.test_receive(1)
    pos = [-3.141592654+0.17551645190320445]
    self.socket.send("movej([%s, %s, %s, %s, %s, %s], a=2.0, v=2.0)\n" % (
    i = 0
    while (i == 0):
      results = self.read_socket_stream()
      if results.values[35] <= pos[0]+0.005 and results.values[35] >= pos[
        f =  Force('192.38.66.252', 12345)
        f.bias()
        break
    self.socket.close()
    myfile = open("data.txt", "a")
    myfile.write('%s, %s, %s, %s, %s, %s\n' % (results.values[30],results.
    myfile.close()

  elif counter == 3: # Rotate to fourth position (~-180 degress)
    self.connect()
    results = self.test_receive(1)
    pos = [-4.712388981+0.17551645190320445]
    self.socket.send("movej([%s, %s, %s, %s, %s, %s], a=2.0, v=2.0)\n" % (
    i = 0
    while (i == 0):
      results = self.read_socket_stream()
      if results.values[35] <= pos[0]+0.005 and results.values[35] >= pos[
        f =  Force('192.38.66.252', 12345)
        f.bias()
        break
    self.socket.close()
    myfile = open("data.txt", "a")
```

```
    myfile.write('%s, %s, %s, %s, %s, %s\n' % (results.values[30],results.
    myfile.close()

  else:
    print "An error occured in the rotate function"


def collect(self,turncounter): #Make the robot pick up a plate from a hol
  self.connect()
  #Move to position for collecting plate
  pos = [-1.26525439665243500,-1.44560270287730370,-1.68035001330557070,
  self.socket.send("movej(%s, a=1.0, v=0.5)\n" % pos)
  i=0
  while (i < 5): #While loop, which controls that the robot have moved in
    results = self.read_socket_stream()
    if results.values[i+30] <= pos[i]+0.001 and results.values[i+30] >= p
      i = i + 1

  self.socket.close()
  time.sleep(0.5)
  #Remove bias/gravity on force sensor
  f =  Force('192.38.66.252', 12345)
  f.bias()
  #Approach to table
  self.approach_z_x(-1)
  #Activate Suctionscop
  print ""
  print "########################################"
  print "###        Securing plate        ###"
  print "########################################"
  print ""
  time.sleep(3)
  self.decouple("z",0.10,turncounter)

def deliver(self): #Drops off the plate in a holder
  self.connect()
  #Move to position for delivering plate
  pos = [-0.58933449904424062,-2.35443412600472210,-0.80623840453672335,
  self.socket.send("movej(%s, a=1.0, v=0.5)\n" % pos)
  i=0
  while (i < 5): #While loop, which controls that the robot have moved in
   results = self.read_socket_stream()
   if results.values[i+30] <= pos[i]+0.001 and results.values[i+30] >= po
```

```
        i = i + 1
    self.socket.close()
    time.sleep(0.5)
    #Remove bias/gravity on force sensor
    f =  Force('192.38.66.252', 12345)
    f.bias()
    #Approach the table
    self.approach_z_x(-1)
    #Deactivate Suctionscop
    print ""
    print "#########################################"
    print "###       Releasing plate       ###"
    print "#########################################"
    print ""
    time.sleep(3)

  def move_to_deburr_pos(self): #Moves the robot to the deburring tool with
    self.connect()
    results = self.test_receive(1)
    postool = results.values[35]
    #Move to position for deburring the plate
#    pos = [0.33146529146213632,-2.70883406010032957,-0.88330808564727037,
    pos = [0.33146529146213632,-2.70883406010032957,-0.88330808564727037,-
#    pos = [0.8447,0.1583,0.09008,0.0,2.35,0.0]
    myfile = open("data.txt", "a")
    myfile.write("%.17f,%.17f,%.17f,%.17f,%.17f,%.17f\n" %(pos[0],pos[1],po
    myfile.close()
    self.socket.send("movej(%s, a=1.0, v=0.5)\n" % pos)
#    self.socket.send("movel(p[%f,%f,%f,%f,%f,%f],a=1.0, v=0.5)\n" % (pos[0
    i=0
    while (i < 5):
      results = self.read_socket_stream()
      if results.values[i+30] <= pos[i]+0.001 and results.values[i+30] >= p
        i = i + 1
    self.socket.close()

  def deburr(self,turncounter): #Runs the four sides of a plate over the de
    self.initialize()
    print ""
    print "#########################################"
    print "###       Deburring plate       ###"
    print "#########################################"
    print ""
```

```
        #The deburring of the first edge start
        self.move_to_deburr_pos()
        #Approaching the deburr machine
        while turncounter < 4:
          self.rotate(0) #Rotates the plate to the first position
          time.sleep(0.5) #The robot has to be completly stopped before removin
          #Removes bias/gravity from force sensor
          f =  Force('192.38.66.252', 12345)
          f.bias()

          self.approach_zx_x(-1,1,2,4) #Moves the plate against the deburring t
          self.translate(-0.005,0,0.005,0,0,0,125./3.) #Moves a little away fro
          time.sleep(0.5) #The robot has to be still before removing bias
          f.bias()
          self.approach_zx_x(-1,-1,0,5) #Moves the plate against the deburring
          time.sleep(0.5)

          self.approach_zx_x(-1,1,2,4) #Moves the plate back against the deburr
          self.translate(0.0,-0.2,0.0,5.0,turncounter,1,125.0) #Moves the robot
          self.decouple("Z",0.10,0) #Lift the robot away from the tool
          turncounter = turncounter + 1
          if turncounter < 4: #Rotates the TCP to the next edge to deburr
            self.rotate(turncounter)
          else:
            self.rotate(0)

#       Comments from edge 1 has to be copied here
        #The deburring of the second edge start
        self.move_to_deburr_pos()
        time.sleep(0.5)
        f.bias()
        self.approach_zx_x(-1,1,2,4)
        f.send_to_socket()
        force = f.read_socket_stream()
        myfile1 = open("force.txt", "a")
        myfile1.write("%f,%f,%f\n" %(force[0],force[1],force[2]))
        myfile1.close()
        self.translate(-0.005,0,0.005,0,0,0,125./3.)
        time.sleep(0.5)
        f.bias()
        self.approach_zx_x(-1,-1,1,5)
        f.send_to_socket()
```

```
        force = f.read_socket_stream()
        myfile1 = open("force.txt", "a")
        myfile1.write("%f,%f,%f\n" %(force[0],force[1],force[2]))
        myfile1.close()
        time.sleep(0.5)
        self.approach_zx_x(-1,1,2,4)
        self.translate(0.0,-0.2,0.0,2.0,turncounter,1,125.0)
        self.decouple("Z",0.10,0)
        turncounter = turncounter + 1
        if turncounter < 4:
          self.rotate(turncounter)
        else:
          self.rotate(0)

#       Comments from edge 1 has to be copied here
        self.move_to_deburr_pos()
        time.sleep(0.5)
        f.bias()
        self.approach_zx_x(-1,1,2,4)
        f.send_to_socket()
        force = f.read_socket_stream()
        myfile1 = open("force.txt", "a")
        myfile1.write("%f,%f,%f\n" %(force[0],force[1],force[2]))
        myfile1.close()
        self.translate(-0.005,0,0.005,0,0,0,125./3.)
        time.sleep(0.5)
        f.bias()
        self.approach_zx_x(-1,-1,0,5)
        f.send_to_socket()
        force = f.read_socket_stream()
        myfile1 = open("force.txt", "a")
        myfile1.write("%f,%f,%f\n" %(force[0],force[1],force[2]))
        myfile1.close()
        time.sleep(0.5)
        self.approach_zx_x(-1,1,2,4)
        self.translate(0.0,-0.2,0.0,2.0,turncounter,1,125.0)
        self.decouple("Z",0.10,0)
        turncounter = turncounter + 1
        if turncounter < 4:
          self.rotate(turncounter)
        else:
          self.rotate(0)
```

```
#       Comments from edge 1 has to be copied here
        self.move_to_deburr_pos()
        time.sleep(0.5)
        f.bias()
        self.approach_zx_x(-1,1,2,4)
        f.send_to_socket()
        force = f.read_socket_stream()
        myfile1 = open("force.txt", "a")
        myfile1.write("%f,%f,%f\n" %(force[0],force[1],force[2]))
        myfile1.close()
        self.translate(-0.005,0,0.005,0,0,0,125./3.)
        time.sleep(0.5)
        f.bias()
        self.approach_zx_x(-1,-1,1,5)
        f.send_to_socket()
        force = f.read_socket_stream()
        myfile1 = open("force.txt", "a")
        myfile1.write("%f,%f,%f\n" %(force[0],force[1],force[2]))
        myfile1.close()
        time.sleep(2)
        self.approach_zx_x(-1,1,2,4)
        self.translate(0.0,-0.2,0.0,2.0,turncounter,1,125.0)
        self.decouple("Z",0.10,0)
        turncounter = turncounter + 1
        if turncounter < 4:
          self.rotate(turncounter)
        else:
          self.rotate(0)


class Results: #Program that converts the recieved data (binary) into data
  def __init__(self, time, values):
    self.time = time
    self.values = values

  def __repr__(self):
    return '<Results time="%s" values="%d" />' % (self.time, len(self.value
```

F.0.3 force.py

```
# TCP client
import numpy
from numpy import *
```

```
import socket
socket.setdefaulttimeout( 5.0 )
import time
import struct

class Force:
  def __init__(self, ip, port): #Init of the Force program, By Orn & Einir
    self.ip = ip
    self.port = port
    self.addr = (ip,port)


  def connect(self): #Connector, Partly by Orn & Einir
    self.socket = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
    try:
      self.socket.connect((self.ip, self.port))
    except socket.error:
      print "Socket Error in force.py"
      print ""
      print "Remember to turn on the VB. script on the PC running the force
      print ""


  def establish_connection(self): #Connector, By Orn & Einir
    self.connect()


  def test_receive(self, n): #Test of connection, Partly by Orn & Einir
    for i in range(n):
      try:
        data = self.read_socket_stream()
      except Exception,e:
        print i, "Error: ", e, " trying to reconnect"
        self.connect()
      return data


  def read_socket_stream(self): #Reads out data, Partly by Orn & Einir
    try:
      data,addr = self.socket.recvfrom(45)
    except socket.timeout:
      print ""
      print "Socket timeout in force.py, line 50"
```

```
      print ""
      return [0.0,0.0,0.0,0.0]
    first = data[0:12]
    second = data[13:25]
    third = data[26:38]
    stamp = data[39:len(data)]
    data2 = [self.commaToDot(first),self.commaToDot(second),self.commaToDo
    i = 0
    while i < 3:
      if data2[i] > 150.0 or data2[i] < -150.0:
        data2[i] = '0.0'
        print "Force reading on ", i," is out of bounce"
      i = i + 1
    return data2


  def send_to_socket(self): #Send 1 (flag) to server, By Orn & Einir
    data = "1"
    try:
      self.socket.send(data)
    except socket.timeout:
      print ""
      print "Socket timeout in force.py, line 68"
      print ""


  def send_to_socket_init(self): #Send init to server, By Orn & Einir
    data = "clear"
    self.socket.send(data)


  def commaToDot(self,s): #Converts from comma to dot notation, By Orn & E
    comma = s.find(',')
    dot = s.find('.')
    if (comma > -1):
      if (dot < 0):   # no dots. comma separates decimals
        s = s.replace (',','.')
    return float(s)

  def bias(self): #Removes bias if sensor measures more than -+0.1 Newton
    self.establish_connection()
    self.send_to_socket()
    force = self.read_socket_stream()
```

```
    i=0
    while (i < 2):
      if force[i] < -0.1:
        self.send_to_socket_init()
      if force[i] > 0.1:
        self.send_to_socket_init()
      i = i+1
```

F.0.4 force_test.py

```
# TCP client
import numpy
from numpy import *
import socket
socket.setdefaulttimeout( 1.0 )
from time import *
import time
from force import Force

i = 0
f = Force('192.38.66.252', 12345)
f.establish_connection()
f.bias()
myfile = open("force_test.txt", "a")
myfile.write("\n### New run ###\n")
while(i < 1500):
  f.send_to_socket()
  data = f.read_socket_stream()
  myfile.write("%s\n" % (data))

  i = i + 1
  print "%f" % i
myfile.close()
f.socket.close()
exit("\n Bye, data can be analyzed in force_test.txt\n")
```

www.elektro.dtu.dk

Department of Electrical Engineering
Automation and Control
Technical University of Denmark
Ørsteds Plads
Building 348
DK-2800 Kgs. Lyngby
Denmark
Tel: (+45) 45 25 38 00
Fax: (+45) 45 93 16 34
Email: info@elektro.dtu.dk